(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 May 2003 (08.05.2003)

PCT

(10) International Publication Number
WO 03/038486 A2

(51) International Patent Classification⁷: G02B 6/00

(21) International Application Number: PCT/GB02/04912

(22) International Filing Date: 30 October 2002 (30.10.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0126007.4 30 October 2001 (30.10.2001) GB
0203146.6 8 February 2002 (08.02.2002) GB
0222622.3 28 September 2002 (28.09.2002) GB

(71) Applicant *(for all designated States except US)*: **SOUTHAMPTON PHOTONICS LIMITED** [GB/GB]; Phi House, Enterprise Road, Chilworth Science Park, Southampton SO16 7NS (GB).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **SHAIFUL, Alam** [BD/GB]; 148 B Broadlands Road, Swaythling, Southampton SO17 3AR (GB). **GRUDININ, Anatoly** [RU/GB]; 69 Burgess Road, Bassett, Southampton SO16 7AL (GB). **YLA-JARKKO, Kalle** [FI/GB]; 36 Arthurs Gardens, Hedge End SO30 2NG (GB). **GODFREY, Ian** [GB/GB]; 15 Kestrel Close, Marchwood, Southampton SO40 4XL (GB). **TURNER, Paul** [GB/GB]; 29 Sovereign Way, Boyatt Wood, Eastleigh SO50 4SA (GB). **MOORE, Jonathan** [GB/GB]; Flat 8, Parkside Gardens, 87 St Mary's Street, Southampton SO14 1LZ (GB). **CODEMARD, Christophe** [FR/GB]; Flat 9, Arundel House, 21 Lawn Road, Portswood, Southampton SO17 2ER (GB). **HORLEY, Ray** [GB/GB]; Canada Cottage, Canada Road, West Wellow, Hampshire SO51 6DD (GB). **SAHU, Jayaunta, Kumar** [IN/GB]; 5 Rayners Garden, Swaythling, Southampton SO16 2JG (GB). **RICHARDSON, David** [GB/GB]; 1 Midanbury lane, Bitterne Park, Bitterne, Southampton SO18 4HY (GB). **NILSSON, Lars, Johan, Albinsson** [SE/GB]; 10 Elm Close, Bassett Avenue, Bassett, Southampton SO16 7DT (GB). **RENAUD, Cyril** [FR/GB]; 39 Barnwood Close, London W9 2RF (GB). **SELVAS-AGUILAR, Romeo** [MX/GB]; 60 Harefield Road, Swaythling, Southampton SO17 3TH (GB).

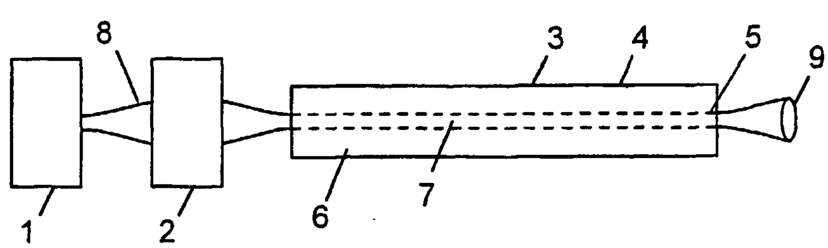
(74) Agent: **JONES, Graham, Henry**; Graham Jones & Company, 77 Beaconsfield Road, Blackheath, London SE3 7LG (GB).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: AN OPTICAL LIGHT SOURCE



(57) Abstract: An optical light source comprising a laser diode (1), a beam shaping optics (2), and an amplifying fibre (3), wherein the amplifying fibre (3) comprises a waveguide (4) comprising a core (5) and a cladding (6), wherein the waveguide (4) is doped with a rare earth dopant (7), and wherein the laser diode (1) can produce optical pump power (8) which is coupled to the waveguide (4) by the beam shaping optics (2).

WO 03/038486 A2

Declaration under Rule 4.17:
— *of inventorship (Rule 4.17(iv)) for US only*

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

AN OPTICAL LIGHT SOURCE

Field of the Invention

This invention relates to an optical light source, an optical amplifier, and a fibre laser.

Background of the Invention

There is a demand for an optical light source for pumping optical amplifiers, lasers and other amplifying optical devices. There is a related demand for optical amplifiers that can output powers of 100mW to 10W, or higher powers, and can amplify many wavelength channels simultaneously with high reliability and low cost per wavelength channel. There is a related demand for optical amplifiers with low-polarisation dependent gain.

Conventional optical amplifiers use single-mode optical fibre whose core is doped with one or more rare-earth ions such as Erbium. These amplifiers are pumped by single-mode pump diodes and hence they provide limited power output that is insufficient for multi-channel WDM transmission systems. In addition, conventional amplifiers are prone to the failure of pump sources, requiring several pump sources to be contained within the amplifier in order to provide certainty of pumping even in the event of pump failures. The pump sources have a single-mode waveguiding stripe which operates with high power densities. The higher the power density in the stripe, the more difficult it is to achieve high reliability. The pump source also need to be wavelength stabilised which is achieved either by using Peltier coolers which control the wavelength indirectly via temperature or by fiber Bragg grating that provide an optical feedback (~5-10%) at certain wavelength locking the output wavelength of the laser.

The power output of conventional optical amplifiers has recently been increased by the introduction of pump modules containing several semiconductor lasers whose outputs are wavelength division multiplexed into a single optical fibre. Although the output power obtainable from such an optical amplifier containing one of these pump modules is sufficient for amplifying many channels simultaneously, the approach is expensive, is currently limited in powers to around 1 W, and offers limited pump redundancy.

The cost issue of optical amplifiers is also a problem as the networks expand into the metropolitan areas, the expansion being driven by the insatiable demand for bandwidth for internet, data, mobile phones and cable television. Prior art optical amplifiers are too expensive and this is currently limiting the expansion of the networks.

Cladding pumped Ytterbium (Yb) doped fibre lasers operating at around 977nm have been the subject of significant technical and experimental activity in recent years. Despite obvious attractions of such sources – as pumps for erbium doped fibre amplifiers (EDFAs) and as stand-alone lasers operating at the shortest wavelength available from cladding-pumped silica fibre lasers – there are no reports on practical, user-friendly, realizations. The principal requirement for practical implementations of high power 977nm fibre lasers is to reach high enough population inversions, since otherwise emission occurs on the quasi-four level transition around 1040nm, with large reabsorption at the two-level 977nm transition. Additionally, Yb-doped fibre lasers are known as being notoriously noisy, with poor relative intensity noise (RIN) characteristics that significantly narrow their range of applications.

Erbium-doped fibre amplifiers (EDFAs) have revolutionized optical communications over the last ten years. The increasing need for capacity drives the

amplification requirements, namely operation over the full C-Band with low noise and short transient times and low cost.

The most common approach to EDFA pumping is to use single-mode laser diodes at 980 or 1480nm. However, a high channel-count means higher output power, therefore more laser diodes, which increases the cost and complexity of the EDFA. Cladding-pump fiber technology offers a cost-effective solution to high power pumping. However, directly cladding-pumped EDFAs are sensitized (co-doped) with ytterbium in order to improve the pump absorption. Furthermore, additional co-doping with phosphorous is required for efficient energy transfer from ytterbium to erbium. Unfortunately phosphorous leads to substantial spectral gain narrowing from the blue end of the gain spectrum, which makes erbium ytterbium co-doped optical amplifiers less suitable for WDM applications. Additionally, compared to traditional EDFAs, ytterbium co-doped directly cladding-pumped EDFAs have a higher noise figure, which also holds back field deployment.

It is an aim of the present invention to obviate or reduce the above mentioned problems.

Summary of the Invention

According to a non-limiting embodiment of the present invention, there is provided an optical light source comprising a laser diode, beam shaping optics, and an amplifying optical fibre, wherein the amplifying optical fibre comprises a waveguide comprising a core and a cladding, wherein the waveguide is doped with a rare earth dopant, and wherein the laser diode is able to produce optical pump power which is coupled to the waveguide by the beam shaping optics.

The beam shaping optics may comprise a first lens. The first lens can be formed on the end of the amplifying optical fibre.

The beam shaping optics may comprise a second lens. The second lens can be a cylindrical lens. The cylindrical lens can be a cylindrical microlens which may have a shape, such as circular, elliptical or hyperbolic, designed to transform some particular given input light distribution into some desired output light distribution. The cylindrical lens may have a uniform refractive index profile, or may have a graded refractive index profile such as parabolic.

The laser diode can be a multimode laser diode. The laser diode can comprise at least one singlemode laser diode. The laser diode can comprise at least one a diode bar. The laser diode can comprise at least one diode stack.

The laser diode can emit 0.1W to 50W of optical pump power. The laser diode can emit 0.5W to 5W of optical pump power.

The cladding can have an outer diameter in the range 10um to 100um. The cladding can have an outer diameter in the range 15um to 50um.

The core and/or cladding can be doped with at least one of germanium, phosphorous, boron, aluminium and fluoride.

The core can be configured to be a single mode waveguide.

The optical pump power can facilitate optical radiation from the rare earth dopant in the waveguide.

The optical radiation from the rare earth dopant in the waveguide can be coupled to an amplifying optical device, wherein the amplifying optical device is one of an optical

amplifier, a laser or a distributed feedback laser, and wherein the amplifying optical device is configured to be pumped by the optical radiation.

The optical radiation from the rare earth dopant in the waveguide can be coupled to a plurality of amplifying optical devices via an optical coupler, and wherein the amplifying optical devices are configured to be pumped by the optical radiation.

The cladding may be circular. The cladding may be substantially rectangular. The cladding may have a non-circular shape.

The core may be centrally located in the cladding. The core may be offset from the centre of the cladding.

The optical radiation from the rare earth dopant in the waveguide can be coupled to an optical amplifier and wherein the optical radiation can be used as a pump source for the optical amplifier.

The optical radiation from the rare earth dopant in the waveguide can be coupled to a plurality of optical amplifiers via an optical coupler, and wherein the optical radiation can be used as a pump source for the optical amplifiers.

The amplifying optical fibre can comprise a microstructured mesh surrounding the cladding. The microstructured mesh may be sealed at either end of the amplifying optical fibre – for example by heating the amplifying optical fibre with an electric arc, a flame or a laser. A glass ferrule may be placed onto either end of the amplifying optical fibre prior to applying heat. The glass may be silica.

The optical light source can comprise feedback means for providing feedback in the waveguide, the waveguide being a laser. The feedback means can be a reflector. The reflector can be formed from a cleave in the amplifying optical fibre. The reflector can be

a fibre Bragg grating. The reflector can be a dichroic filter. The dichroic filter may be deposited on the end of the amplifying optical fibre.

The amplifying optical fibre can be configured as a source of amplified spontaneous emission.

The rare earth dopant can be contained in the core. The rare earth dopant can be contained in the cladding. The rare earth dopant can be contained in both the core and the cladding.

The rare earth dopant can be configured in a region surrounding the centre of the waveguide. The region surrounding the centre of the waveguide can be a ring surrounding the core. The ring can have a thickness in the range 1 to 10um.

The rare earth dopant can comprise Yb and it is preferable that the laser diode emits at a wavelength that is absorbed by the Yb. The optical light source may comprise a dichroic filter that reflects in the wavelength range 975nm to 980nm, and wherein the optical light source comprises a second port, the optical light source being an optical amplifier for 975nm to 980nm radiation. It is preferable that the waveguide is configured to emit optical radiation in a wavelength range from 975nm to 980nm, wherein the optical radiation is coupled to at least one erbium-doped optical amplifier via an optical coupler, and wherein the optical radiation is used as a pump source for the optical amplifier. It is preferred that the Yb is configured in a region surrounding the centre of the waveguide.

The amplifying optical fibre may comprise an absorber to attenuate unwanted optical radiation. The absorber may be a saturable absorber or an unsaturable absorber. It is preferred that the rare earth dopant is Yb and the absorber is samarium configured to absorb unwanted optical radiation occurring in the wavelength region 1020nm to 1050nm.

The absorber may be in the core, the cladding, or in both the core and the cladding. It is preferred that the Yb and the absorber is configured in a region surrounding the centre of the waveguide. It is preferred that the amplifying optical fibre comprises a microstructured mesh surrounding the cladding and that the cladding has an outer diameter in the range of 15μm to 75μm. The cladding may have an outer diameter in the range 25μm to 35μm.

The rare earth dopant can comprise Erbium and it is preferable that the laser diode emits at a wavelength that is absorbed by the Erbium.

The rare earth dopant can comprise Erbium codoped with Ytterbium, and it is preferable that the laser diode emits at a wavelength that will be absorbed by the Ytterbium.

The rare earth dopant can comprise Neodymium and it is preferable that the laser diode emits at a wavelength that is absorbed by the Neodymium.

The rare earth dopant can comprise Thulium and it is preferable that the laser diode emits at a wavelength that is absorbed by the Thulium.

The rare earth dopant can comprise Praseodymium and the laser diode emits at a wavelength that is absorbed by the Praseodymium.

The rare earth dopant can be selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, or is Erbium codoped with Ytterbium, or is doped with a transition metal or semiconductor.

The invention also provides an optical amplifier comprising the optical light source. The optical amplifier may be configured to have low polarisation dependent gain.

The invention also provides an optical fibre laser comprising the optical light source.

The invention also provides a method for pumping a plurality of optical amplifiers having low polarisation dependent gain, wherein each optical amplifier comprises a pump input, the method comprising the steps of providing an optical light source according to the present invention, and coupling the optical light source to the pump inputs.

The invention also provides a method for pumping a plurality of fibre lasers each comprising a pump input, the method comprising the steps of providing an optical light source according to the present invention, and coupling the optical light source to the pump inputs.

The invention can also be considered to be a source of amplified spontaneous emission for pumping an optical fibre amplifier or laser.

Brief Description of the Drawings

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 is a diagram of a light source according to the present invention;

Figure 2 shows the light source coupled to an optical amplifier;

Figure 3 shows the light source coupled to a plurality of optical amplifiers;

Figure 4 shows waveguide comprising feedback means;

Figure 5 shows a ring-doped amplifying fibre;

Figure 6 shows an optical fibre being stretched by the application of heat and tension;

Figure 7 shows a lens formed on the end of an optical fibre;

Figure 8 shows a second fibre with a curved fibres being spliced to an amplifying fibre;

Figure 9 shows a cylindrical lens on the end of an amplifying fibre;

Figure 10 shows a beam shaping optics comprising a second lens;

Figure 11 shows a microstructured mesh sealed at either end of an amplifying fibre;

Figure 12 shows a glass ferrule placed onto an amplifying fibre;

Figure 13 shows an amplifying optical fibre with a non-circular cladding;

Figure 14 shows an amplifying optical fibre with an offset core;

Figure 15 shows the absorption and emission spectra for ytterbium ions in silica glass;

Figure 16 shows the dependence of threshold power 161 on cladding diameter for a silica optical fibre having a ytterbium-doped single mode core;

Figure 17 shows a two-emitter pump module;

Figure 18 shows the output spectra of the pump module;

Figure 19 shows the output power as a function of laser diode current for the pump module;

Figure 20 shows a cross-section of a ytterbium-doped jacketed air-clad (JAC) fibre;

Figure 21 shows a fibre laser comprising the JAC fibre;

Figure 22 shows the output power versus launched power for a fibre laser and an amplified spontaneous emissions (ASE) source that comprise the JAC fibre;

Figure 23 shows the temporal behavior of the fibre laser comprising the JAC fibre;

Figure 24 shows an amplified spontaneous emission (ASE) source comprising the JAC fibre;

Figure 25 shows the output spectrum of the ASE source;

Figure 26 shows the temporal behavior of the ASE source;

Figure 27 shows an erbium doped fibre amplifier (EDFA) that is pumped with the ASE source;

Figure 28 shows EDFA's spectral gain characteristic for two different input power levels;

Figure 29 shows the EDFA's spectral noise figure characteristic;

Figure 30 shows the cross-section of ring-doped ytterbium JAC fibre;

Figure 31 shows an ASE source comprising the ring-doped JAC fibre;

Figure 32 shows a fibre laser comprising the ring-doped JAC fibre;

Figure 33 shows the output power as a function of absorbed power for the ASE source and fibre laser;

Figure 34 shows the spectral dependence of output power for the ASE source and the fibre laser;

Figure 35 shows a measurement of relative intensity noise with frequency for the ASE source and the fibre laser;

Figure 36 shows an optical amplifier comprising a gain clamping laser diode and which amplifier is pumped with the ASE source;

Figures 37 to 40 show the spectral output response of the optical amplifier when the input was between two and 32 separate wavelength channels;

Figure 41 shows the dependence of gain and noise figure measured as a function of total input power;

Figure 42 shows the spectral dependence of gain for different levels of gain clamping power;

Figure 43 shows the spectral dependence of polarization dependent gain when the optical amplifier is pumped with the ASE source and a laser-diode;

Figure 44 shows the power variation at the output of the EDFA when the input power increased by 15dB;

Figure 45 shows the doping profiles of the fibre shown in Figure 20;

Figure 46 shows the doping profiles of the fibre shown in Figure 30;

Figure 47 shows an amplifying optical device comprising a first port and a second port;

Figure 48 shows an amplifying optical device comprising a thin film filter;

Figure 49 shows an arrangement in which pump power is amplified by the amplifying optical device of Figure 48;

Figure 50 shows a preform assembly comprising solid rods and capillaries;

Figure 51 shows an optical fibre drawn from the preform assumebly of Figure 50;

Figure 52 shows a preform assembly comprising a non-circular preform; and

Figure 53 shows an optical fibre drawn from the preform assembly of Figure 52.

Detailed Description of Preferred Embodiments of the Invention

Figure 1 shows an optical light source comprising a laser diode 1, a beam shaping optics 2, and an amplifying fibre 3, wherein the amplifying fibre 3 comprises a waveguide 4 comprising a core 5 and a cladding 6, wherein the waveguide 4 is doped with a rare earth dopant 7, and wherein the laser diode 1 can produce optical pump power 8 which is coupled to the waveguide 4 by the beam shaping optics 2.

The amplifying fibre 3 is preferably made from silica or silicate glass. The amplifying fibre 3 can be made from phosphate glass or other soft glasses.

The laser diode 1 can be a multimode laser diode. The laser diode 1 can be a singlemode laser diode. The laser diode 1 can be a diode bar. The laser diode 1 can be a diode stack. The laser diode 1 can comprise a combination or a plurality of laser diodes, diode bars and/or diode stacks.

The laser diode 1 can emit 0.1W to 50W of optical pump power. The laser diode 1 can emit 0.5W to 5W of optical pump power.

The beam shaping optics 2 can comprise a first lens 71. The first lens 71 can be formed on the end of the amplifying fibre 3. Examples of forming lenses on the ends of fibres by applying tension and heating the fibre in an electric arc can be found in US Patent 4,589,897, which is incorporated herein by reference. Figure 6 shows the principle. Tension is applied to the amplifying fibre 3 and heat is applied. This results in a neck 61 being formed in the amplifying fibre 3. The amplifying fibre 3 then separates into two. Further application of heat results in the first lens 71 being formed on the amplifying fibre 3 as shown in Figure 7. An alternative method for forming a spherical lens is described in US Patent 4,345,930. Alternatively, a second fibre 81 having a curved surface 82 can be fusion spliced or joined to the amplifying fibre 3 as shown in Figure 8. This arrangement is described in US patent 4,737,006.

The amplifying optical fibre 3 will generally have a circular fundamental mode and a laser diode an elliptical mode. The first lens 71 may be a cylindrical lens 91 formed by polishing the end of the amplifying fibre 3 or the second fibre 81. A cylindrical lens 91 is

shown in Figure 9 and is further described in US patent 6332053 which is hereby incorporated by reference.

The beam shaping optics 2 can comprise a second lens 100 as shown in Figure 10. The second lens 100 can be a cylindrical lens. The cylindrical lens can be a cylindrical microlens which may have a shape, such as circular, elliptical or hyperbolic, designed to transform some particular given input light distribution 101 into some desired output light distribution 102. The cylindrical lens may have a uniform refractive index profile, or may have a graded refractive index profile such as parabolic. Examples of cylindrical lenses and their application to coupling to laser diodes can be found in US patent 5,080,706 which is incorporated herein by reference.

The cladding 6 can have an outer diameter in the range 10um to 100um. The cladding 6 can have an outer diameter in the range 15um to 50um. The cladding 6 can be circular. The cladding 6 can be non-circular. Advantageously, a non-circular cladding 6 can increase the overlap of light propagating in the cladding 6 with the core 5.

The core 5 and/or cladding 6 can be doped with germanium, phosphorous, boron, aluminium and/or fluoride.

The core 5 can be configured to be a single mode waveguide. Alternatively the core 5 can be configured to be a multimode waveguide. The core 5 can be circular, ring-shaped, elliptical, oval, rectangular, or in the form of an irregular or a regular polygon.

The core 5 can be configured centrally with respect to the cladding 6. The core 5 can be configured off-centre with respect to the cladding 6. Advantageously, a non-circular cladding 6 can increase the overlap of light propagating in the cladding 6 with the core 5.

The optical pump power 8 can stimulate optical radiation 9 from the rare earth dopant 7 in the waveguide 4. The optical radiation 9 may be amplified spontaneous emission. The optical radiation 9 may be dominated by stimulated emission.

Figure 2 shows the optical radiation 9 from the rare earth dopant 7 in the waveguide 4 coupled to an optical amplifier 20, wherein the optical radiation 9 is used as a pump source for the optical amplifier 20. The coupling is achieved using a lens 21. It is preferable that the coupling is achieved using an optical fibre coupler.

Figure 3 shows the waveguide 3 coupled to a plurality of amplifying optical devices 33 via an optical fibre 31, a plurality of optical couplers 32. The optical radiation 9 is used as a pump source for the amplifying optical devices 33. The amplifying optical devices 33 can be optical amplifiers, lasers, distributed feedback fibre lasers or distributed Bragg reflector fibre lasers.

The amplifying fibre 3 can comprise a microstructured mesh 111 surrounding the cladding 6. As shown in Figure 11, the microstructured mesh 111 may be sealed at either of end 112, 113 of the amplifying fibre 3 – for example by heating the amplifying fibre 3 with an electric arc, a flame or a laser. The first lens 71 may be formed on the end 112 in order to facilitate coupling to a laser diode. The end 113 may be cleaved as shown in Figure 11, or fusion spliced to an output fibre (not shown). The cleaved end provides a flat surface for subsequent coating of the end face of the fibre, for example with a dichroic mirror.

As shown in Figure 12, a glass ferrule 120 may be placed onto the amplifying fibre 3 prior to applying heat. A reflecting material 123 may be placed onto the glass ferrule. The reflecting material 123 may be a metal such as chrome, silver or gold, and the metal

may be deposited using electroless plating techniques. This configuration has advantages in that pump light not absorbed in the amplifying fibre 3 can be reflected back through the amplifying fibre 3.

Figure 4 shows feedback means 40 for providing feedback in the waveguide 4, the waveguide 4 being a laser. The feedback means 40 can be a reflector. The reflector can be formed from a cleave in the amplifying fibre 3. The reflector can be a fibre Bragg grating. The reflector can be a mirror. The reflector can be a dichroic mirror.

The amplifying fibre 3 can be configured as a source of amplified spontaneous emission.

Referring to Figure 1, the rare earth dopant 7 can be contained in the core 5. The rare earth dopant 7 can be contained in the cladding 6. The rare earth dopant 7 can be contained in the core 5 and in the cladding 6.

Figure 5 shows the rare earth dopant 7 configured in a region 50 surrounding the centre of the waveguide 4. The region 50 surrounding the centre of the waveguide 4 is shown as a ring 51 surrounding the core 5. The ring 51 can have a thickness 52 in the range 1 to 10um.

The rare earth dopant 7 can comprise Ytterbium (Yb) and it is preferable that the laser diode 1 emits at a wavelength that is absorbed by the Yb. It is preferable that the waveguide 4 is configured to emit optical radiation in the wavelength range 970nm to 980nm. It is preferred that the wavelength range is from 975nm to 988nm. The Yb can be configured in a region surrounding the centre of the waveguide 4. Alternatively, the Yb can be configured in a region that is offset from the center of the waveguide 4 which can be advantageous to increase the absorption of pump power. The optical radiation can be

coupled to at least one erbium-doped optical amplifier via an optical coupler, and wherein the optical radiation is used as a pump source for the optical amplifier. This embodiment has particular advantages for pumping optical amplifiers as wells as lasers and distributed feedback lasers. There are advantages of configuring the waveguide 4 as a source of amplified spontaneous emission when pumping these devices. These advantages include wavelength stability, lower amplitude noise, higher reliability and reduced cost owing to their lower power densities in the waveguiding stripes. In addition, it is not necessary to temperature stabilise the laser diode which further reduces cost and improves reliability because a peltier device is not required. The unpolarised nature of the ASE output when used as a source of pump radiation for lasers or amplifiers provides significant advantages in terms of noise reduction and reduction in polarisation dependant gain.

The amplifying fibre 3 may comprise an absorber to attenuate unwanted optical radiation. The absorber may be a saturable absorber or an unsaturable absorber. It is preferred that the rare earth dopant is Yb and the absorber is samarium configured to absorb unwanted optical radiation occurring in the wavelength region 1020nm to 1050nm. The absorber may be in the core, the cladding, or in both the core and the cladding. It is preferred that the Yb is configured in a region surrounding the centre of the waveguide. It is preferred that the amplifying fibre comprises a microstructured mesh surrounding the cladding and that the cladding has an outer diameter in the range of 15μm to 75μm. The cladding may have an outer diameter in the range 25μm to 35μm.

Figure 13 shows an amplifying fibre 130 comprising a core 5, a non-circular cladding 136, an air cladding region 111, and an outer jacket 133. The air cladding region 111 comprises holes 135, 139 that extend longitudinally along the amplifying fibre 130.

The holes 135 are formed from the inside of capillaries used to fabricate the amplifying fibre 130. The holes 139 are formed from the interstitial spaces between the capillaries used to fabricate the amplifying fibre 130. In certain embodiments, the amplifying fibre 130 may comprise only holes 135 (if the interstitial holes 139 are closed up by the application of a vacuum in the fibre drawing process), or only interstitial holes 139 (if rods are used instead of capillaries, or if the capillaries are collapsed by the application of vacuum in the fibre drawing process).

Advantages of the non-circular cladding 136 are that it better matches the near field of typical laser diodes, and that there will be an increased overlap between the modes guided by the non-circular cladding 136 and the core 5. The non-circular cladding 136 can be rectangular, square, triangular, D-shaped, or a circular shape comprising flats that are machined prior to preform assembly. The dimensions of the non-circular cladding 136 can be 10μm to 500μm for the minor axis, and 150μm to 1000μm for the major axis.

Figure 14 shows an amplifying fibre 140 in which the core 5 and region 131 is offset from the center of the cladding 141. The amplifying fibre 140 is an example of a jacketed air-clad (JAC). The amplifying fibre 140 comprises an air cladding region 142 and an outer jacket 143 that can advantageously be configured to ensure that the core 5 is substantially central with respect to the outer circumference of the outer jacket 143 (note the centre lines 149 shown in Figure 14). Having a core that is concentric with the outside of the fibre is advantageous for fusion splicing, whilst having a core that is not central with respect to the cladding is advantageous because of the increased overlap of the cladding modes with the core 5 and/or the optional region 131 that surrounds the core 5. This

configuration thus combines the increased mode overlap advantages of an offset core with the fusion splicing advantages arising from concentric cores.

The core 5 may comprise the rare-earth dopant 7. Alternatively, or additionally, the amplifying fibre 130 may comprise a region 131 that surrounds the core 5 and this region 131 may comprise the rare-earth dopant 7. Figure 13 also shows an outer region 132 that surrounds the region 131. The outer region 132 may be doped with a saturable or an unsaturable absorber. The region 131 may be doped with Ytterbium ions and the outer region 132 may be doped with samarium, and the amplifying fibre 130 used as a source of radiation at around 977nm. Such a source can be susceptible to radiation induced or fed back at 1035nm to 1060nm, and the samarium is useful to absorb this radiation.

Referring to each of the embodiments described above, the rare earth dopant 7 can comprise Erbium (Er) and it is preferable that the laser diode 1 emits at a wavelength that is absorbed by the Er.

The rare earth dopant 7 can comprise Er codoped with Yb, and it is then preferable that the laser diode 1 emits at a wavelength that will be absorbed by the Yb.

The rare earth dopant 7 can comprise Neodymium (Nd) and it is preferable that the laser diode 1 emits at a wavelength that is absorbed by the Nd.

The rare earth dopant 7 can comprise Thulium (Tm) and it is preferable that the laser diode 1 emits at a wavelength that is absorbed by the Tm.

The rare earth dopant 7 can comprise Praseodymium (Pr) and the laser diode 1 emits at a wavelength that is absorbed by the Pr.

The rare earth dopant 7 can be selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, or is Erbium codoped with Ytterbium, or is doped with a transition metal or semiconductor.

Cladding-pumping with high-power multimode diode pump sources is the preferred way to power-scale fibre lasers. In cladding-pumped devices the overlap of the pump field with the gain medium is small and therefore a large amount of dopant is required to absorb the pump. However before the pumping creates enough gain at 977 nm in a Yb-doped laser, undesired gain at longer wavelengths (typically 1035nm to 1100nm) with weak re-absorption becomes so high that spurious oscillations cannot be suppressed. This unwanted gain restricts fibre length and thus pump absorption, resulting in low slope efficiency. To achieve lasing at 977 nm one has to ensure that the gain at 1040 nm is lower than the threshold for spurious lasing and that the pump intensity, and thus power, is high enough to invert more than 50% of the Yb-ions. Both pump threshold power and gain at ~1040 nm are proportional to the inner cladding area and for a practical device with, say, a threshold below 400 mW and a pump absorption of 6 dB, the inner cladding diameter should be below 25 μm [J. D. Minelly *et al.*, OFC'2000, Paper PD2, Baltimore, USA (2000)]. For efficient pump launch into such a small inner cladding its numerical aperture should be as high as possible.

In our device we have chosen a jacketed air-clad (JAC) geometry, since it not only offers a route to achieving a numerical aperture (NA) of 0.7 or higher, but also offers the robustness and reproducibility of conventional silica fibre technology [J. K Sahu, *et al.* Electron. Lett. **37,** 1116 (2001)].

Yb-ions have a strong emission cross-section at 976 nm. Thus using low cost broad area pump diodes operating at 915 nm and a double clad fibre, high power radiation can be achieved in the wavelength region that is preferred for pumping EDFAs.

Figure 15 shows the absorption spectrum 151 and emission spectrum 152 of Yb-ions in silica glass. The emission 152 and absorption 151 cross sections at around 976 nm are equal so in order to achieve lasing one has to reach a 50% population inversion.

Transparency pump intensity (i.e. the pump intensity required for a 50% population inversion) is approximately $2.5\cdot 10^4$ W/cm^2 or 10 W for a double clad fibre with 200 μm pump cladding. To make such a source practical one has to employ a high brightness pump source.

Figure 16 shows the dependence of threshold power 161 as a function of pump cladding diameter 162 for a Yb-doped single-mode core in silica glass. Assuming an acceptable threshold for such a pump source is around 500 mW, then Figure 16 shows that the pump cladding diameter 162 should be below 30 μm. From the data presented in Figure 16, one can conclude that today's commercially-available, pig-tailed, high-power, broad-area pump diodes (1.5 – 2.5 W in 100 μm diameter fibre) are not suitable for the practical realization of cost-effective fibre based pump sources.

The realization of a 976 nm fibre pump source using broad-area pump diodes is even more difficult because of unwanted gain at around 1010 nm to 1080nm (see Figure 15) which shows that the Yb-doped glass system is quasi four level at these wavelengths.

There are two main requirements for an efficient laser. First the pump threshold P_{th} should be small compared with the available pump power P_p and second the slope efficiency η with respect to launch power must be high.

In cladding pumped devices the overlap of the pump field with the gain medium is small and therefore a large amount of dopant to absorb the pump is required. However before the pumping creates enough gain at 978 nm in such a laser, undesired gain at longer wavelengths (1030 –1080 in case of Yb-doped fibre lasers) with weak re-absorption becomes so high that spurious oscillations cannot be suppressed. This unwanted gain restricts fibre length, pump absorption and results in low slope efficiency.

In a homogeneously broadened gain medium such as Yb-doped silica fibres, the gain G (in dB) can be written as [J. Nilsson *et al.*, Opt. Lett. **23**, 355-357 (1998)]

$$G = kN_0 A_d \Psi_d(\lambda)\{[\sigma_e(\lambda) + \sigma_a(\lambda)]n_2 - \sigma_a(\lambda)\}L, \qquad (1)$$

where $k = 4.343$, N_0 is the concentration of active ions, L is the fibre length, σ_e and σ_a are the emission and absorption cross sections, respectively and n_2 is the fraction of active ions that are excited. Finally Ψ_d is the value of the normalized modal intensity averaged over doped area A_d (in other words if P is the incident pump power then $P\Psi_d$ is the average intensity in the doped area). It can be shown that the unwanted gain at 1030 nm can be expressed as

$$G^{1030} = 0.25G^{976} + 0.72\beta\alpha_{0p}^{p}, \qquad (2)$$

where $\beta = \Psi_d^s/\Psi_d^p = A_{cladding}/A_{core}$ and α_{0p}^{p} is the pump absorption.

The 1030 nm gain is proportional to the cladding-to-core area ratio $A_{cladding}/A_{core}$ and grows rapidly with pump absorption α_{0p}^{P}.

Thus in order to suppress lasing at 1030 nm one has to ensure that $G^{1030} < 40$ dB i.e. when lasing cannot be initiated by spurious reflections or Raleigh scattering. Taking the core to cladding diameter ratio equal to 3 and assuming that the single pass gain at 976 nm is 7 dB (lasing from one cleaved end) then the pump absorption will be in the region of 6 dB or 75% of available pump power, which is sufficiently high to allow for an efficient device. In practical terms, the pump cladding diameter should not exceed 25 μm since in order to achieve low splice loss to commercial fibres the doped core should be single-moded at 976 nm and the typical diameter of a core in a standard telecom-fibre is in the region of 8 μm.

Figure 17 shows a pump module 171. In order to achieve low threshold and high efficiency, a pump source 171 was used based on a two-emitter assembly, that is the pump source 171 used two laser diode chips whose outputs were combined together and launched into the Yb-doped fibre. Similar pump module can be procured Milon Laser Co. from St. Petersburg in Russia, or from New Optics Limited based in the United Kingdom. The New Optics Limited product has a product name "Ultra-6". Each laser diode is capable of delivering up to 2 W of optical power at 915 nm. Launching efficiency into a 30 μm diameter, 0.3 NA optical fibre should be greater than 75%. The optical spectrum 180 of the pump module 171 is shown in Figure 18 in which the measured output power 181 is plotted against wavelength 182. Figure 19 shows the output power 191 measured as a function of the laser diode current 192.

There are several key requirements for a rare-earth doped fibre that is intended to operate in a three level transition: the doped fibre should have high efficiency (greater than 50% and preferably greater than 70%); there should be high pump absorption; the pump

cladding area should be below 600 μm^2 (i.e. core-to-cladding diameter ratio should be more than 0.3); and the pump cladding numerical aperture (NA) should be high enough to allow high coupling efficiency from broad-stripe pump diodes.

Figure 20 shows a jacketed air clad (JAC) fibre 200 that meets these criteria. The Yb-doped fibre 200 has a raised index core 201 co-doped with boron and germanium, a pure silica inner cladding 202, a mesh 203 comprising two rings of longitudinally extending circular holes 204 and an outer silica jacket 205. The doped core diameter was 8 μm and the NA = 0.1. The germanium doping makes the core 201 photosensitive which is advantageous for writing fibre Bragg gratings into the core 201 with ultraviolet light. The diameter of the pure silica inner cladding 202 was 28 μm. To ensure a high NA the mesh 203 was fabricated with two layers of silica capillary tubes stacked around a preform inside a silica jacket. The strand thickness – ie the diameters of the silica capillary tubes in the resulting JAC fibre 200 was 1 to 2 μm. The JAC fibre 200 has a polymer coating 206 (not shown) that has a refractive index greater than the refractive index of the silica jacket 205. Note that it may actually be beneficial to have a polymer coating with a refractive index less than the refractive index of the silica jacket 205. Figure 45 shows the dopant profiles 450 of the JAC fibre 200 as a function of radius 455. The JAC fibre 200 comprises a region 451 doped with germania (in order to make the core 201 photosensitive) and a region 452 doped with Ytterbium. The region 452 included the core 201 as well as a ring 453 surrounding the core 201. Note that germania would have been lost from the centre of the JAC fibre 200 during the collapsing stages of the (earlier) preform manufacturing process, leading to the well-known refractive index dip at the centre of the fibre 200. This refractive index dip is not shown in Figure 45. Referring again to Figure 20, the 915 nm

pump absorption was 1 dB/m. The pump cladding NA (ie the effective numerical aperture of pump light transmitting along the pure silica inner cladding 202) was measured at 0.4 and 0.5 depending on the length of the JAC fibre 200 under test.

There are two approaches in the development of a high-power pump source. One is based on the development of a fibre laser where the pump wavelength is fixed by a wavelength selective reflector (such as a fibre Bragg grating or a filter). Another way is to configure the fibre as a source of amplified spontaneous emission ASE – ie an ASE source. Both approaches have pros and cons: fibre lasers ultimately deliver more power and are more efficient, whereas an ASE source is simpler in design, does not require any wavelength selective elements and is less noisy.

Figure 21 shows a fibre laser 210 comprising the pump source 171 and the JAC fibre 200. A laser cavity 211 was formed by a first fibre Bragg grating 212 and a second fibre Bragg grating 213. The first fibre Bragg grating 212 was written directly into the core 201 and the second fibre Bragg grating 213 was written into a photosensitive single mode optical fibre 216 procured from FiberCore Limited which had a second-mode cut-off at 920nm and which was sliced to the JAC fibre 200 at splice 214. The reflectivity of the second grating 213 was 20% and the reflectivity of the first grating 212 was 15% to 20%. The length 215 of the cavity 211 was 4m.

Figure 22 shows the output power 221 of the fibre laser 210 versus the launched power 222 defined as the power that is coupled into the inner cladding 202 from the pump source 171. The slope efficiency 223 with respect to launched power 222 was 37%. This relatively low slope efficiency can be explained by the fact that the device length was kept short in order to prevent unwanted lasing at 1030 nm.

Figure 23 shows the temporal dependence of the output power 221 of the fibre laser 210 which clearly demonstrates beating of longitudinal modes as evidenced by the noise peaks 232. The low Q-value of the laser cavity and relatively long device length have resulted in temporal instability of the output signal 221. The characteristic time 233 is set by the laser cavity length 215 and in this example the characteristic time 233 is equal to 40 ns which corresponds to the cavity roundtrip time. Such an instability might be acceptable for a pump source intended to be used in EDFA but will significantly restrict range of possible applications of fibre-based pumps.

Figure 24 shows a high power ASE source 240 comprising the pump source 171, the JAC fibre 200. The configuration of the ASE source 240 is almost identical to that of the fibre laser 210 except there are no gratings and the output end 241 of the source 240 is angle-cleaved.

The output power 224 of the ASE source 240 is shown plotted against launched power 222 in Figure 22. The slope efficiency 225 with respect to the launched power 222 is 27%. Figure 25 shows the normalised intensity 251 of the ASE source 240 as a function of wavelength 253. There is a strong output centred at around 977nm with a spectral width 252 of around 3nm. The output of the ASE source is situated at the peak of the 980nm absorption band of erbium ions in silica glass. Moreover, the output of the ASE source will have a spectral characteristic that will be substantially stable with respect to ambient temperature fluctuations thus removing the need for external wavelength stabilisation (eg provided by fibre Bragg gratings) as is commonly used in sources for pumping EDFAs and other erbium-doped devices.

Figure 26 shows the normalised output power 251 as measured over time 252. The maximum output power available from the ASE source 240 was 400 mW. The ASE source 240 provides relatively high power, has a stable output wavelength with temperature and time, and provides a low-noise output that has none of the beating that was observed in Figure 23. Note that the parameters of the JAC fibre 200 had not been optimised and further development of doped fibres as well as JAC fibres will result in significant increase of output power up to 1500 mW or higher.

Figure 27 shows an erbium doped amplifier EDFA 270 that was pumped by the ASE source 240. The EDFA 270 comprises tap couplers 271, photodiodes 272, isolators 273, WDM couplers 274, erbium doped single mode fibre 275, control electronics 276 and a variable optical attenuator 277. Signal light is input at the input port 278 and output at the output port 279. Pump power 2711 was delivered by the 978 nm ASE fibre source 240 via a 1 x 4 pump splitter 2710. The pump splitter 2710 was constructed from optical fibre couplers.

The gain and noise figure of the EDFA 270 was measured as a function of wavelength 281 at signal input power levels of –11dBm and –31dBm. Figure 28 shows the gain 282 measured at –11dBm and the gain 283 measured at –31dBm. Figure 29 shows the noise figure 291 measured at –11dBm. Surprisingly, the gain and noise figure characteristics were nearly identical to those obtained when pumping with a commercially-available 980nm semiconductor pump source designed specifically for pumping EDFAs. Advantageously, the fibre pump source 240 is capable of pumping up to four EDFAs providing a saturated power of 13 dBm.

Figure 30 shows a preferred embodiment of a ring-doped JAC fibre 300. The JAC fibre 300 comprises a core 301 that is doped with Germania, a rare-earth doped region 302 surrounding the core 301 that is doped with Yb, a silica inner cladding 303, longitudinally extending holes 307, a thin glass mesh 304 where the mesh 304 has a wall thickness 305 that is around 0.5um to 2um – ie comparable to the intended wavelength of operation, and a supporting silica jacket 306. The diameter of the JAC fibre 300 is approximately 125um. The design results in very low pump leakage from the silica inner cladding 303 and hence provides a high effective numerical aperture. The core is single-moded with a cut-off of 950 nm. In order to suppress unwanted gain at 1040 nm we have utilized ring-doping of Yb ions [J. Nilsson *et al.*, Opt. Lett. **23**, 355-357 (1998)], [A. S. Kurkov *et al.*, OAA Technical Digest, OMA4-1 (2001)]. The pump absorption is 6 dB/m.

Figure 46 shows the dopant profiles 460 of the JAC fibre 300 as a function of radius 465. The JAC fibre 300 comprises a region 461 doped with germania (in order to make the core 301 photosensitive) and a region 462 doped with Ytterbium that surrounds the core 301. Note that diffusion mechanisms during the preform manufacturing process can lead to diffusion of the germania into the region 462 and diffusion of Ytterbium into the region 461. Note also that germania would have been lost from the centre of the JAC fibre 300 during the collapsing stages of the (earlier) preform manufacturing process, leading to the well-known refractive index dip at the centre of the fibre 300. This refractive index dip is not shown in Figure 46. Similar fibres can also be fabricated with phosphorous doping of the core 301, or we have also experimented with pure silica cores surrounded by a Ytterbium-doped gain medium. Alternatively, the core can be ring-doped with germania or phosphorous and co-doped with Ytterbium. The emission cross-section

spectrum of Yb ions in silica glass has a relatively narrow (approximately 4 nm wide) peak centred around 977 nm. High-power emission is possible from around 975nm to around 980nm by taking several different approaches. For example, a laser can be formed using broadband feedback from reflectors such as dichroic mirrors or fibre Bragg gratings, where the wavelength selection arises from the shape of the emission cross-section. Alternatively, a laser can be formed using wavelength selective feedback from at least one of these reflectors. Wavelength selective feedback can be achieved using a filter such as a fibre Bragg grating. It is also possible to simply pump a Ytterbium doped fibre in order to realise a source of amplified spontaneous emission.

Figure 31 shows an ASE source 310 comprising a laser diode 311 emitting at 915nm, optics 312, the JAC fibre 300, an optical fibre 313. The JAC fibre 300 was 3.25m long. The length is very dependent upon fibre design and the amount of pump power that is launched into the fibre. Depending on Yb concentration and disposition, a length between 0.5m and 5m is acceptable. The optical fibre 313 is a photosensitive single mode fibre comprising a photosensitive waveguide 3111 comprising a core and a cladding. Photosensitive fibres for the manufacture of fibre Bragg gratings are available from many different suppliers. Optionally, a fibre Bragg grating 3110 (or other reflector) can be written into the fibre 313 in order to reflect pump radiation at 915nm back into the fibre 300 in order to increase the pump absorption and thus increase the output power. Note that the fibre 313 should preferably have a photosensitive cladding and a photosensitive core in order that the fibre Bragg grating 3110 can be configured to reflect the pump light, most of which would be propagating as cladding modes. This option was not implemented in this experiment. Also note that there is no need to provide either the fibre 313 or for

photosensitivity if there is no intention of writing a grating into the fibre 313. If the fibre 313 is not provided, then the JAC fibre 300 should be antireflection coated and/or cleaved at an angle to prevent back-reflections.

Referring again to Figure 31, the optical fibre 313 is shown cleaved at an angle 314 in order to prevent the signal out 315 reflecting back into the JAC fibre 300. This makes the output 315 nearly uni-directional even with a simple perpendicular cleave (4% reflecting) in the pump launch end 316 of the JAC fibre 300. The optics 312 comprised both cylindrical and spherical lenses which may be a graded refractive index (GRIN) lens and preferably at least one dichroic filter 319 that is highly transmissive between 900-950nm to allow the 915nm pump radiation to be transmitted from the laser diode 311 to the JAC fibre 300, and highly reflective between 970nm-1070nm to attenuate any unwanted signals being fed back to the laser diode 311. The dichroic filter 319 can be configured at an angle so that the reflected light between 970nm- 1070nm is not reflected into the fibre 300. Such unwanted signals can damage a laser diode.

It is possible to configure one of the at least one dichroic filters 319 as an end-mirror for the JAC fibre 300, that is highly-reflecting at around 975 to 980nm. In such case, additional measures are preferable to prevent light in the 1020 – 1100 nm wavelength range from reaching the diode 311 and from being fed back into the fiber 300. One option is to make the 975 nm highly reflective filter highly transmissive in the range 1020 – 1100 nm. That suppresses feedback into the fiber in the 1020 - 1100 nm range. It can be combined with a rejection filter between the dichroic cavity-filter and the diode 311 that is highly reflective in the 1020 – 1100 nm wavelength range (and optionally at around 975 to 980 nm), and configured at an angle such that it does not reflect light back into the fiber

300. Alternatively, the rejection filter can be positioned between the 975 nm highly reflective filter and the fiber 300. In that case, the rejection filter must not reject 975 nm radiation; i.e., it should be highly transmissive at 975 nm.

There are many possible variations of arrangements of the at least one dichroic filter 319 that perform the essential tasks, namely reflecting 975 nm light back into the fiber, transmitting 915 nm pump light from the diode 311 to the fiber 300, and preferably rejecting light in the 1020 – 1100 nm wavelength range (i.e., does not feed it back into the fiber 300 and prevents it from reaching, and damaging, the pump diode 311). If necessary, 975 nm rejection filters can also be used, outside the design path for 975 nm light that prevents 975 nm light firm reaching and damaging the diode 311.

It is preferable to seal the end 316 of the JAC fibre 300 as shown in Figure 30 by heating the fibre 300 in order to prevent moisture from ingressing into the holes 307. The end 316 can then be cleaved (as shown) or left with a curved surface, or first lens 71 as described with reference to Figure 11. The holes 307 were collapsed at the other end 317 of the JAC fibre 300 when the fibres 300, 313 were fusion spliced together. It may also preferable to deposit the dichroic mirror 319 on the fibre end 316.

Figure 32 shows a fibre laser 320. The fibre laser 320 is similar to the ASE source 310 but comprises a fibre Bragg grating 323 in the photosensitive single mode fibre 322 with reflectivity of approximately 10% at 977nm (although the reflectivity could have been advantageously reduce to around 1%), and the optics 321 comprises a cylindrical and focussing lenses and a broadband dichroic filter 322 that provides feedback into the laser 320. The JAC fibre 300 was 0.75m long, but 0.25m to 2m may be more preferable for different fibre designs. Preferably the cylindrical and spherical lenses are coated with

coatings that provide broadband antireflection in the wavelength range from around 910nm to 1000nm. Preferably, the broadband dichroic filter 322 should provide high transmission at 915nm and high reflectivity at 975 to 980nm. It may also be beneficial to provide high rejection in a wavelength range of around 1020nm to 1100nm to prevent these longer wavelengths either being fed back into the fibre 300 and causing instabilities or into the laser diode 311. High rejection can be provided with an additional dichroic filter having high reflectivity at 1020nm to 1100nm and configured to reflect the 1020nm to 1100nm light out of the signal and/or pump path (see discussion with respect to Figure 31). The broadband dichroic mirror 322 is preferably deposited on the end of the JAC fibre 300 after the air holes are sealed by application of heat (which can be achieved for example by placing the fibre 300 into an electric arc). Alternatively, the dichroic mirror 322 can be deposited on a thin glass plate and then attached to the end 316 of the JAC fibre 300, for example using solder. The laser 320 may optionally comprise a reflector 324 for reflecting back pump energy at 915nm in order to increase pump absorption. The reflector 324 may be a fibre Bragg grating, or may be implemented with a narrowband dichroic mirror place between the JAC fibre 300 and the fibre 313 – for example, deposited on the end 317 of the JAC fibre 300. The latter implementation is preferable because the reflector 324 is preferably a multimode pump reflector that is configured to reflect the 915nm light propagating in the cladding 303.

At the output end in Figure 32 the 975 to 980 nm reflectivity should be in the range 0.2 – 20%, and the 1020 – 1100 nm reflectivity should be as low as possible, and preferably lower than the reflectivity at 970nm. It is advantageous to reflect back the pump light with the reflector 324.

Both sources 310, 320 have benefits as well as some drawbacks. The structure of the ASE-source 310 is simple as no external feedback is required to produce emission at 977 nm. Since the output is seeded by spontaneous emission, the relative intensity noise RIN is essentially white, and the output is essentially unpolarized even in the presence of weak polarizing effects. The drawbacks of the ASE-source 310 are a lower efficiency and an inherent sensitivity to back-reflections. This sensitivity to back reflections can be resolved using an isolator attached to the output. On the contrary the fibre laser 320 is less sensitive to back-reflections and has lower threshold and higher efficiency than the ASE-source 310. However, the structure is more complex and there are high RIN peaks at the relaxation oscillations frequency and at frequencies corresponding to the cavity round trip time.

Figure 33 shows the measured output power 331 of the ASE source 310 and the output power 332 of the laser 320 plotted against the absorbed power 333. Figure 34 shows the measured output power 341 of the ASE source 310 and the measured output power 342 of the laser 320 plotted against wavelength 343. Figure 35 shows the relative intensity noise RIN 351 of the ASE source 310 and the RIN 352 of the laser 320 plotted against frequency 353. The suppression of emission at around 1040 nm is more than 20 dB for both the ASE and laser sources 310, 320. The spectral width of the ASE source 310 is 3 to 4 nm and the centre wavelength is situated at 976 nm, which is near the peak of the 980 nm absorption band of erbium-ions in silica glass. The spectral width of the fibre laser 320 was 0.5 nm, mainly determined by the characteristics of the reflective grating 323.

In some applications, such as pumping of distributed feedback DFB fibre lasers [L.B. Fu *et al.*, Technical digest 28th European Conference on Optical Communication

ECOC-2002, Copenhagen, paper 08.3.5 (2002)], the temporal stability of a Yb-doped fibre-based pump source is as important as the wall-plug efficiency and output power. Referring to Figure 35, the ASE-source 310 has no cavity and hence its RIN is white, without any peaks arising, e.g., from relaxation oscillations or other cavity effects. The RIN of the ASE-source 310 is below −130 dB/Hz and thus should not generate any extra contribution to RIN of a DFB fibre laser because the RIN will be integrated over all frequencies of the pump source. Hence, the ASE-source 310 is an ideal pump source for DFB fibre lasers for application in cable television CATV and wavelength division multiplex WDM systems. However, as the shot noise limit of the pump absorption is −153 dB/Hz the RIN below 1 kHz increases with RIN of the pump for all values above the shot noise limits. This may be a concern for some sensing applications for DFB fibre lasers in which the low-frequency range is of specific interest.

As can be seen from Figure 35, the fibre laser pump source 320 has several RIN peaks 354, 355, 356. The relaxation oscillation peak occurs at 450 kHz at a RIN level of −100 dB/Hz. The RIN peak is dependent on the cavity length and hence on the position of the grating output coupler. In our measurements the cavity length was 3.25m. The additional peaks in the RIN spectrum 355, 356 are harmonics of the beat frequency 354 of the longitudinal modes within the laser cavity. Outside the peaks the RIN 352 of the fibre laser 320 is very low and limited only by the sensitivity of the measurement device (~ −145 dB/Hz). Thus by optimising the device length of the fibre laser 320, it should be a suitable pump source for DFB fibre lasers in both analogue CATV and digital WDM systems.

In addition to the flat RIN characteristics, the unpolarized output of the ASE source 310 is also advantageous for pumping. The RIN noise of DFB fibre lasers can be induced

not only by the RIN of the pump but also from fluctuations in its polarization state and frequency.

With 2.5 W of absorbed pump power the laser source 320 was capable of delivering 1.4 W of output power. To our knowledge, this is the highest output power obtained from a single-mode fibre-coupled source at around 980 nm. Both sources 310, 320 are suitable for pumping of DFB fibre lasers and other applications that demand low noise and/or high-power. Such applications include pumping distributed bragg reflector (DBR) fibre lasers and optical amplifiers for telecom, CATV applications, and laboratory instrumentation.

Figure 36 shows an erbium doped amplifier (EDFA) 360 comprising a preamplifier 361 and a booster amplifier 362 connected with a mid-stage gain-flattening filter 363. The EDFA 360 comprises tap couplers 366, an input photodiode 367, an output photodiode 3619, isolators 368, WDM couplers 369, erbium doped fibre 3610, and thin-film pass-band filters 3615. Fibre 3614 provides coupling of residual pump power from the pre-amplifier 361 to the booster amplifier 362. The EDFA 360 has an input 3616 an output 3617, and a pump input 3618. Some of the components in the EDFA 360 can be replaced with similar components having similar functionality, such as hybrid components comprising tap coupler 366, photodiode 367 and an isolator 368.

The pump power for both the pre-amplifier 361 and the amplifier 362 is provided by the ASE source 310 whose output was split through a 75/25 coupler 364. The preamplifier 361 is co-pumped with 200mW while the booster amplifier 362 is counter-pumped with 600mW of power. A wavelength division multiplexer coupler 3612 was connected to the output of the ASE source 310. The wavelength division multiplexing (WDM) coupler 3612 was selected to couple 977nm radiation from the ASE source to the

coupler 364, and undesireable longer wavelength emission at 1035nm to the termination 3613. The termination 3613 is designed to minimize reflection at 1035nm back into the ASE source which can have the effect of inducing instabilities or lasing action. The termination was implemented with a tight coil of optical fibre, but could have been implemented with index matching gel and/or an angle cleave. The WDM coupler 3612 could also have been replaced with another type of filter, such as a blazed grating designed to transmit the desired 977nm radiation, and to attenuate greatly radiation unwanted radiation at 1035nm.

Because of the slow dynamics of the ASE source 310 it is not possible to compensate varying signal loads and transients by modulating the pump power. Instead, a DFB laser diode 365 at 1570nm (outside the transmission band) with a maximum output power of 40mW is used to clamp the gain and control transients in the booster amplifier 362. The power from the DFB laser diode 365 is added and dropped from the amplifier using thin-film WDM couplers 3615. When channels are dropped, the gain compression decreases, causing the output power of remaining channels to increase. Therefore the output of the clamping laser 365 is varied by the control electronics 3611 when channels are added or dropped, so that the available gain (measured using the input photodiode 367 and the output photodiode 3619) remains constant. The fast electronic response time, below 1μs, allows the suppression of fast transients. The advantage of the gain-clamping with the laser 365 within the EDFA gain bandwidth is that only 27mW of optical power is required to control a 10dB drop of input power.

The EDFA 360 was tested with 32 channels each having different central wavelengths that were distributed on the 100GHz ITU grid from 1530.33 to 1555.75nm

and input into the EDFA 360. The total input power of the EDFA 360 was 0dBm, i.e. the power per channel was -15dBm. The EDFA 360 had a saturated output power of +23dBm in the region 1528nm to 1563nm. The total pump power was set at 800mW for all conditions. The gain-flattening filter (GFF) 363 was designed such that the EDFA 360 had a flat gain with 0dBm input power and zero clamping power. The output WDM spectrums show a flat gain from 0dBm (32 channels) down to -15dBm (one channel remaining).

For total signal input power below 0 dBm, the power of the gain-clamping laser diode 365 was adjusted to keep the gain constant at 23 dB. Figures 37, 38, 39 and 40 show output WDM spectra obtained from the EDFA 360 with a different number of channels 371. The gain flatness is better than +/- 0.5 dB for the input power range. The dual-stage configuration and the high pump power available allow for a noise figure better than 5.5dB. A commercial EDFA test system based on time-domain extinction was used for the noise figure measurement. The accuracy of the system for the noise figure measurement is better than 0.3dB. As an example the characteristics of the EDFA 360 for a channel at 1550.92nm are shown in Figure 41 where the gain 411 and noise Figure 412 are plotted versus total input power 413.

Advantageously, the combination of GFF 363, EDFA design and gain clamping using a controllable external source 310, allows the control of the gain tilt of the EDFA 360. Figure 42 shows the gain 421, 422, 423, 424 with eight channels for "clamping powers" of 10mW, 15mW, 16mW and 17mW respectively. The gain tilt, that is the variation in gain 421, 422, 423, 424 with wavelength, decreases with increasing gain clamping power from the DFB laser diode 365.

Figure 43 shows the polarisation dependent gain (PDG) 431, 432 versus wavelength 433 measured using the ASE source 310 and a conventional 980 semiconductor laser diode (not shown) respectively as the pump source of the EDFA 360. The ASE source 310 provides a 0.1dB reduction in the PDG of the EDFA 360. This is particularly significant for high-bit-rate communication systems where low PDG is becoming increasingly important.

The transient behaviour of optical amplifiers is very important in network applications. In particular, the output of the optical amplifier should not vary if another wavelength channel is added or dropped. The transient behaviour of the EDFA 360 shown in Figure 36 was simulated by switching on and off 31 of the 32 wavelength channels with an acousto-optic modulator. The output power of the surviving channel at 1550.92nm was measured using a fiber Bragg grating filter to filter the output power from ASE and other unwanted measurement noise, and a fast photodiode connected to an oscilloscope. The rise and fall times of the measured optical add-drop power applied at the input 3616 were below 500ns.

In order to ensure that the power of the surviving wavelength channel does not vary, it is necessary to provide control signals from the outputs of the photodiodes 367, 3619 to the control electronics 3611 which controls the clamping laser 365 in order to compensate for changes of input signal power caused by adding and dropping channels. The high-speed electronic control of the clamping laser diode 365 enables the overshoot and undershoot to be controlled below 0.5dB for 15dB of input power added or dropped. This is demonstrated by the measurement results of Figure 44, which shows the output power 441 of the EDFA 360 as a function of time 442 when the input power was increased by 15dB.

The settling time 443 for adding 15dBm of input optical power and dropping 15dBm of optical power was less than 100μs for both cases. The gain-clamping power with a single remaining channel (-15dBm input power) was about 35mW at 1570nm.

The EDFA 360 when pumped with the ASE source 310 and when using the combination of the gain clamping diode 365 and control electronics 3611 has excellent characteristics as measured by its low noise, low gain tilt, low polarisation dependent gain, and excellent transient behavior.

Figure 47 shows an amplifying optical device 470 comprising a first port 479, a second port 4710, a JAC fibre 472 comprising a first end 475 and a second end 476, a dichroic mirror 471 a lens 473 and a fibre 474. The JAC fibre 472 may be any of the JAC fibres described herein. Preferably the JAC fibre 472 is JAC fibre 300 which is ring-doped with Ytterbium. The ends 475, 476 are preferably sealed and cleaved as described with reference to figure 11. The fibre 474 is preferably an optical fibre configured to be singlemoded at 980nm. Pump radiation 478 is coupled from the laser diode 311 which emits at 915nm, and is coupled through the dichroic mirror 478 and launched into the JAC fibre 472. The pump radiation excites the Ytterbium ions, and radiation is thereupon emitted from the first and second ports 479, 4710 of the amplifying optical device 470. The amplifying optical device 470 can be configured as an ASE source (see Figure 31) or a fibre laser (see Figure 32). The amplifying optical device 470 can also be configured as an optical amplifier for amplifying signals having a wavelength where the JAC fibre 472 provides gain.

Figure 48 shows an amplifying optical device 480 comprising a pump module 481, an input beam 482, a thin-film filter 483 comprising a dichroic filter 484, isolators 485, a

Figure 50 shows a preform assembly 500 comprising a preform 501, a plurality of solid rods 502, a plurality of capillaries 503, and an outer jacket 504. The preform 501 comprises a core 5 and a cladding 6. The core 5 may be rare-earth doped. The preform may also comprise a separate rare earth doped region similar to that described in previous embodiments. The capillaries 503 are chosen to maximize the fill ratio, that is, to ensure that there are no significant gaps between preform 501, rods 502, capillaries 503 and outer jacket 504. This is achieved by either selecting the preform 501, rods 502, capillaries 502 and outer jacket 504 to have the correct size, or adjusting their diameters by etching, by heating and stretching on a glass lathe, or by reducing their diameter by drawing on a fibre drawing tower prior to assembling the preform assembly 500. If the preform 501 is fabricated using modified chemical vapour deposition (MCVD), then it is usually preferable to reduce its diameter using acid etching. This is because acid etching reduces the size of the cladding 6 while leaving the dimensions of the core 5 untouched. Preferably the capillaries 503 have thin walls in order to increase the volume fraction of air to glass within the annular region separating the rods 502 from the outer jacket 504. Increasing the volume fraction results in increased numerical aperture of the cladding of the resulting fibre. Figure 51 shows a cross-section of the JAC fibre 510 that is drawn from the preform assembly 500. The fibre 510 comprises longitudinally extending holes 511. The cladding 6 is non-circular which is advantageous because of the increased overlap between cladding modes and the core 5.

Figure 52 shows a preform assembly 520 comprising a non-circular preform 521, rods 522, capillaries 523, and an outer jacket 524. The non circular preform 521 can be fabricated by etching a preform manufactured using modified chemical vapour deposition,

and then milling to the required shape using an ultrasonic drill. Figure 53 shows the resulting amplifying fibre 530 that is drawn from the preform assembly 520. The cladding 6 is non-circular which increases the overlap of cladding modes with the core 5 and thus increases pump absorption. Advantageously, the rods 522 can be stress applying rods comprising silica doped with borosilicate. The stress applying rods may also be doped with germania in order to raise the refractive index. The resulting fibre 530 would then be birefringent which is advantageous for polarization maintenance.

The amplifying fibres 510, 530 can be single mode or multimode depending on the size of the core 5.

Figures 51 and 53 show two types of amplifying optical fibres that can be drawn from the preform assemblies 500 and 520 respectively. However, many different designs can be produced from these assemblies. The variations are produce by applying different amounts of pressure and/or vacuum to each individual capillary and also to the interstitial gaps between the rods and capillaries. In addition, capillaries can be sealed prior to the drawing process. These techniques are well documented in the literature concerning the manufacture of holey, microstructured, and photonic bandgap fibres.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance the performance of the apparatus.

The present invention extends to the above mentioned features taken singularly or in any combination.

Claims

1. An optical light source comprising a laser diode, beam shaping optics, and an amplifying optical fibre, wherein the amplifying optical fibre comprises a waveguide comprising a core and a cladding, wherein the waveguide is doped with a rare earth dopant, and wherein the laser diode is able to produce optical pump power which is coupled to the waveguide by the beam shaping optics.

2. An optical light source according to claim 1 wherein the beam shaping optics comprises a first lens.

3. An optical light source according to claim 2 where the first lens is formed on the end of the amplifying optical fibre.

4. An optical light source according to any one of the preceding claims wherein the beam shaping optics comprises a second lens.

5. An optical light source according to claim 4 wherein the second lens is a cylindrical lens.

6. An optical light source according to claim 5 wherein the cylindrical lens is a cylindrical microlens which has a shape designed to transform some particular given input light distribution into some desired output light distribution.

7. An optical light source according to claim 5 or claim 6 wherein the cylindrical lens has a uniform refractive index profile or a graded refractive index profile.

8. An optical light source according to claim 1 wherein the laser diode is a multimode laser diode.

9. An optical light source according to any one of the preceding claims wherein the laser diode emits 0.1W to 50W of optical pump power.

10. An optical light source according to claim 9 wherein the laser diode emits 0.5W to 5W of optical pump power.

11. An optical light source according to any one of the preceding claims wherein the cladding has an outer diameter in the range 10μm to 100μm.

12. An optical light source according to claim 11 wherein the cladding has an outer diameter in the range 15μm to 50μm.

13. An optical light source according to any one of the preceding claims wherein the core and/or cladding is doped with at least one of germanium, phosphorous, boron, aluminium and fluoride.

14. An optical light source according to any one of the preceding claims wherein the core is configured to be a single mode waveguide.

15. An optical light source according to any one of the preceding claims wherein the optical pump power facilitates optical radiation from the rare earth dopant in the waveguide.

16. An optical light source according to any one of the preceding claims wherein the optical radiation from the rare earth dopant in the waveguide is coupled to an amplifying optical device, wherein the amplifying optical device is one of an optical amplifier, a laser or a distributed feedback laser, and wherein the amplifying optical device is configured to be pumped by the optical radiation.

17. An optical light source according to any one of the preceding claims wherein the optical radiation from the rare earth dopant in the waveguide is coupled to a plurality of amplifying optical devices via an optical coupler, and wherein the amplifying optical devices are configured to be pumped by the optical radiation.

18. An optical light source according to any one of the preceding claims wherein the cladding is circular.

19. An optical light source according to any one of claims 1 to 17 wherein the cladding is substantially rectangular.

20. An optical light source according to any one of claims 1 to 17 wherein the cladding has a non-circular shape.

21. An optical light source according to any one of the preceding claims wherein the core is centrally located in the cladding.

22. An optical light source according to any one of claims 1 to 20 wherein the core is offset from the centre of the cladding.

23. An optical light source according to any one of the preceding claims wherein the amplifying optical fibre comprises a microstructured mesh surrounding the cladding.

24. An optical light source according to claim 23 wherein the amplifying optical fibre has two ends, and wherein the microstructure mesh is sealed in at least one of the ends of the amplifying optical fibre.

25. An optical light source according to any one of the preceding claims and comprising feedback means for providing feedback in the waveguide, the waveguide being a laser.

26. An optical light source according to claim 25 wherein the feedback means is a reflector.

27. An optical light source according to claim 26 wherein the reflector is formed from a cleave in the amplifying optical fibre.

28. An optical light source according to claim 26 wherein the reflector is a fibre Bragg grating.

29. An optical light source according to claim 26 wherein the reflector is a dichroic filter.

30. An optical light source according to claim 29 wherein the dichroic filter is deposited on the end of the amplifying optical fibre.

31. An optical light source according to any one of claims 1 to 24 wherein the amplifying optical fibre is configured as a source of amplified spontaneous emission.

32. An optical light source according to any one of the preceding claims wherein the rare earth dopant is contained in the core.

33. An optical light source according to any one of claims 1 to 31 wherein the rare earth dopant is contained in the cladding.

34. An optical light source according to any one of claims 1 to 31 wherein the rare earth dopant is contained in both the core and the cladding.

35. An optical light source according to any one of claims 1 to 31 wherein the rare earth dopant is configured in a region surrounding the centre of the waveguide.

36. An optical light source according to claim 35 wherein the region surrounding the centre of the waveguide is a ring surrounding the core.

37. An optical light source according to claim 36 wherein the ring has a thickness in the range 1 to 10μm.

38. An optical light source according to any one of the preceding claims wherein the rare earth dopant comprises Ytterbium and the laser diode emits at a wavelength that is absorbed by the Ytterbium.

39. An optical light source according to claim 38 and comprising a dichroic filter that reflects in the wavelength range 975nm to 980nm, and wherein the optical light source comprises a second port, the optical light source being an optical amplifier for 975nm to 980nm radiation.

40. An optical light source according to claim 38 wherein the waveguide is configured to emit optical radiation in a wavelength range from 975nm to 980nm, wherein the optical radiation is coupled to at least one erbium-doped optical amplifier via an optical coupler, and wherein the optical radiation is used as a pump source for the optical amplifier.

41. An optical light source according to any one of claims 1 to 37 wherein the rare earth dopant comprises Erbium and the laser diode emits at a wavelength that is absorbed by the Erbium.

42. An optical light source according to any one of claims 1 to 37 wherein the rare earth dopant comprises Neodymium and the laser diode emits at a wavelength that is absorbed by the Neodymium.

43. An optical light source according to any one of claims 1 to 37 wherein the rare earth dopant comprises Thulium and the laser diode emits at a wavelength that is absorbed by the Thulium.

44. An optical light source according to any one of claims 1 to 37 wherein the rare earth dopant comprises Praseodymium and the laser diode emits at a wavelength that is absorbed by the Praseodymium.

45. An optical light source according to any one of claims 1 to 37 wherein the rare earth dopant is selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, or is Erbium codoped with Ytterbium, or is doped with a transition metal or semiconductor.

46. An optical amplifier comprising an optical light source according to any one of the preceding claims.

47. An optical amplifier according to claim 45 and configured to have low polarisation dependent gain.

48. An optical fibre laser comprising an optical light source according to any one of claims 1 to 38.

49. A method for pumping a plurality of optical amplifiers having low polarisation dependent gain, wherein each optical amplifier comprises a pump input, the method

comprising the steps of providing an optical light source according to any one of claims 1 to 38, and coupling the light source to the pump inputs.

50. A method for pumping a plurality of fibre lasers each comprising a pump input, the method comprising the steps of providing an optical light source according to any one of claims 1 to 38, and coupling the optical light source to the pump inputs.

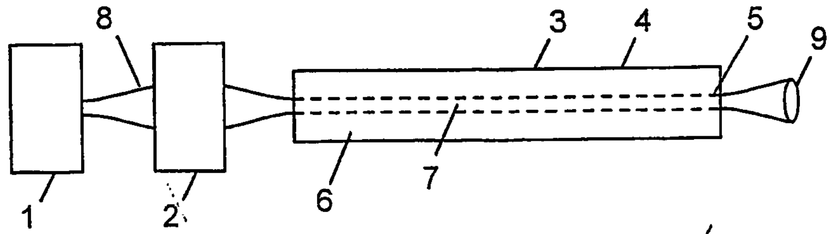


FIG 1 α

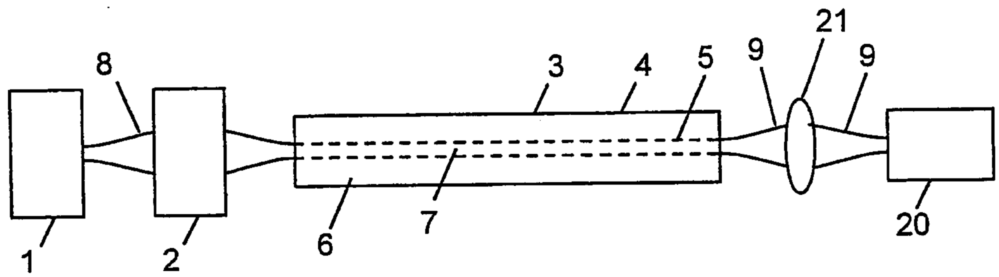


FIG 2

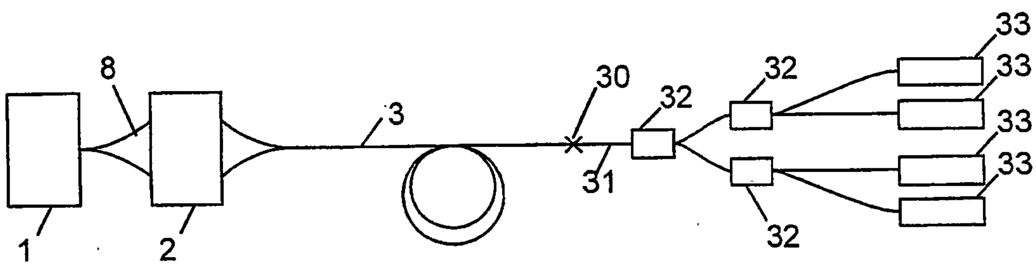


FIG 3

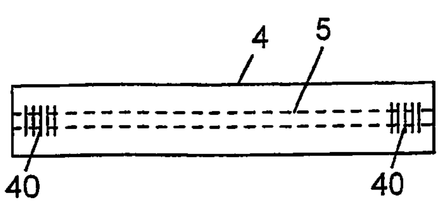


FIG 4

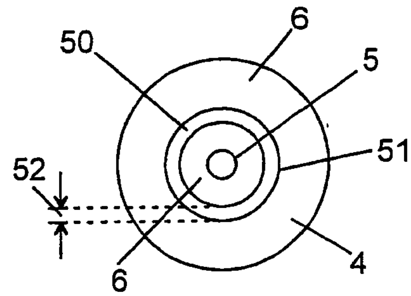


FIG 5

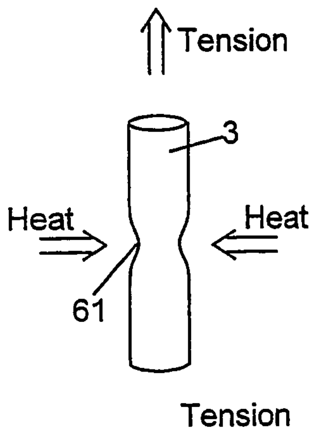


FIG 6

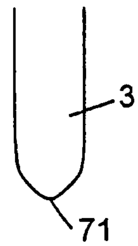


FIG 7

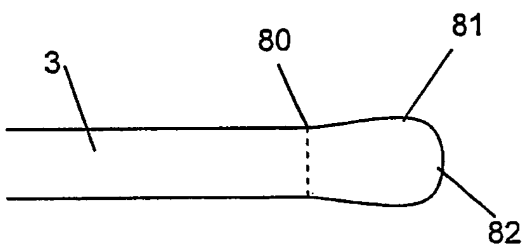


FIG 8

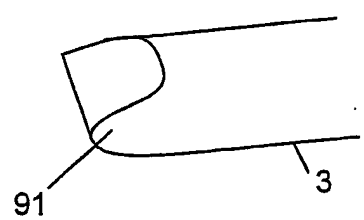


FIG 9

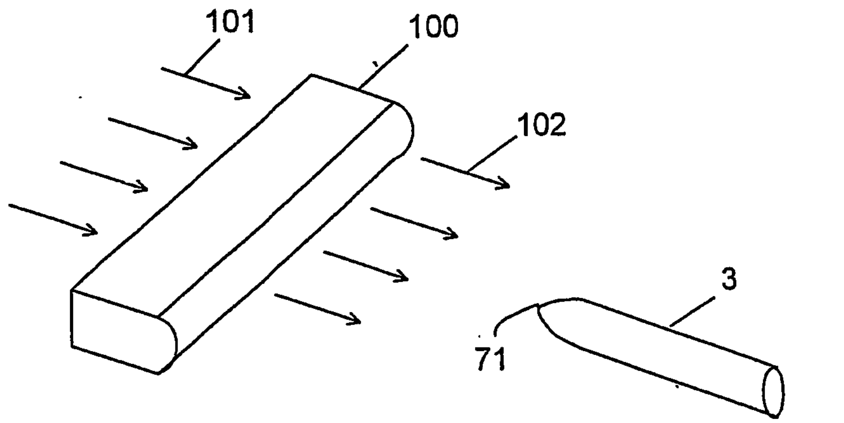


FIG 10

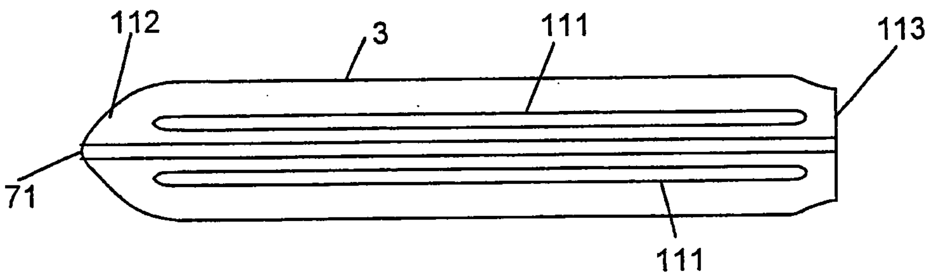


FIG 11

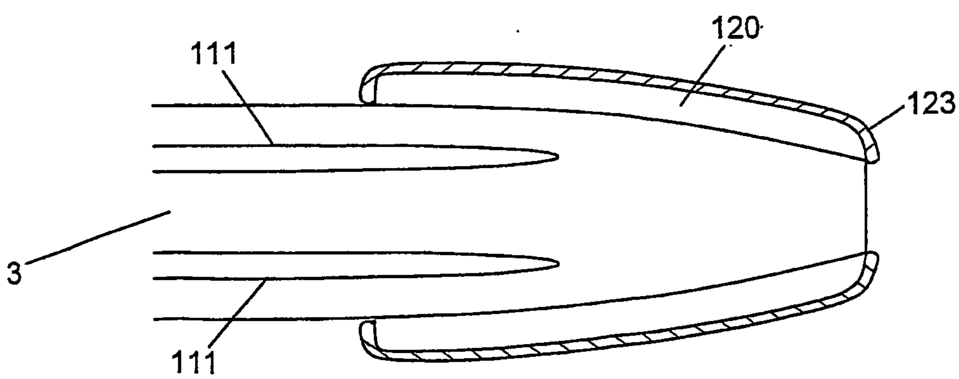


FIG 12

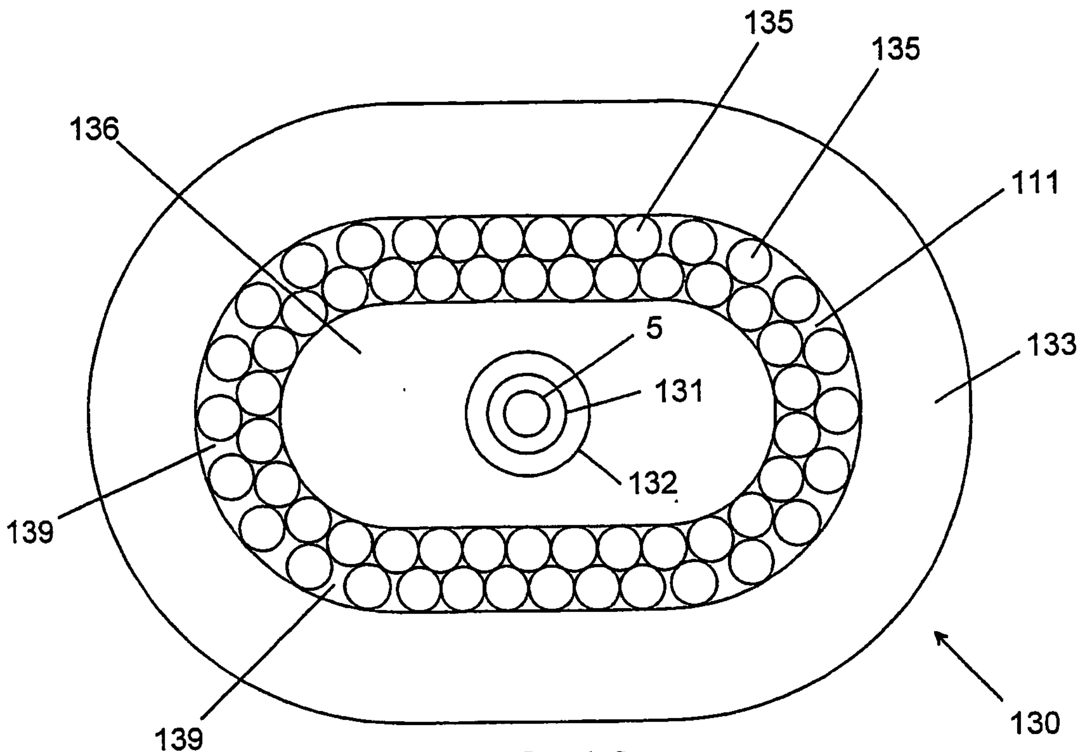

135
135
136
111
5
133
131
132
139
139
130

FIG 13

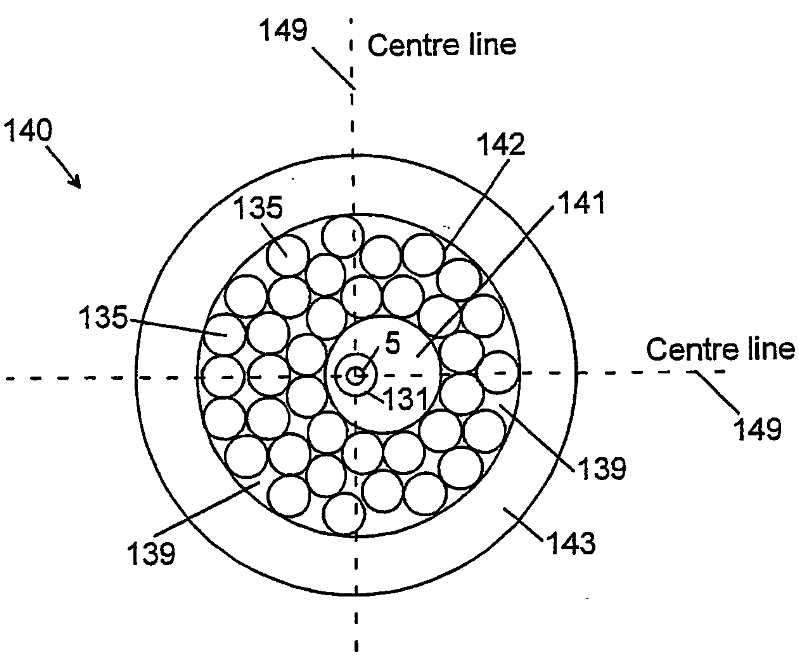
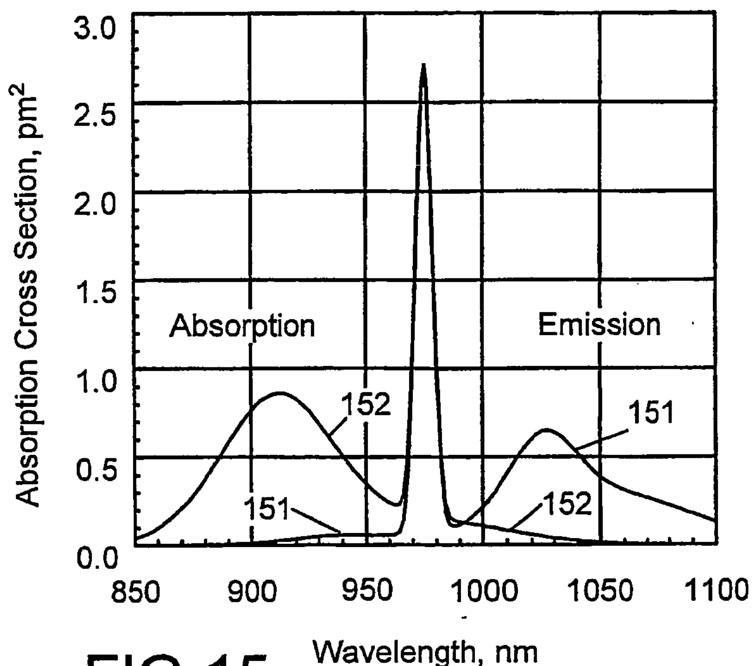
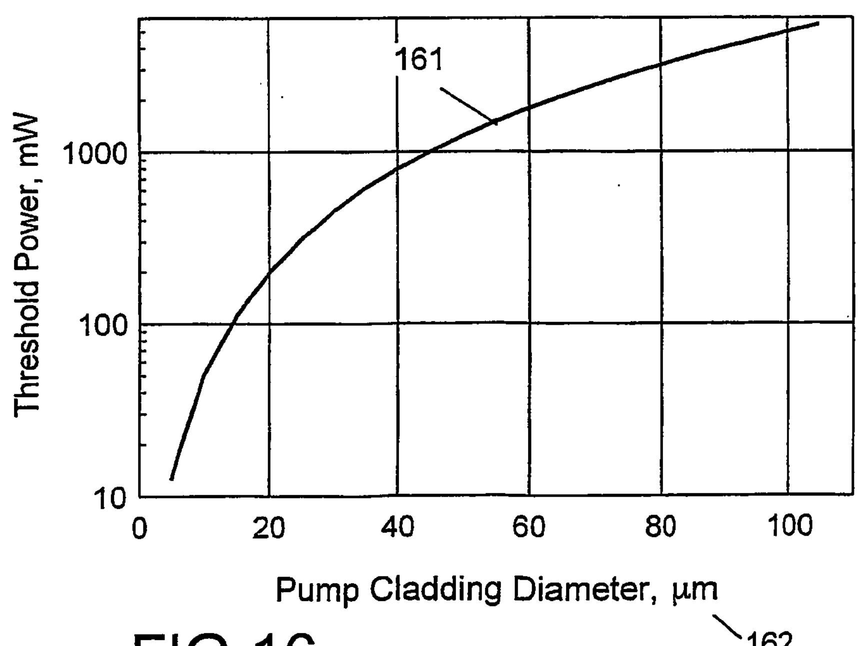

149
Centre line
140
142
135
141
135
5
Centre line
131
149
139
139
143

FIG 14



Absorption Cross Section, pm^2
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Absorption
Emission
152
151
151
152
850
900
950
1000
1050
1100
Wavelength, nm

FIG 15



Threshold Power, mW
1000
100
10
161
0
20
40
60
80
100
Pump Cladding Diameter, µm
162

FIG 16

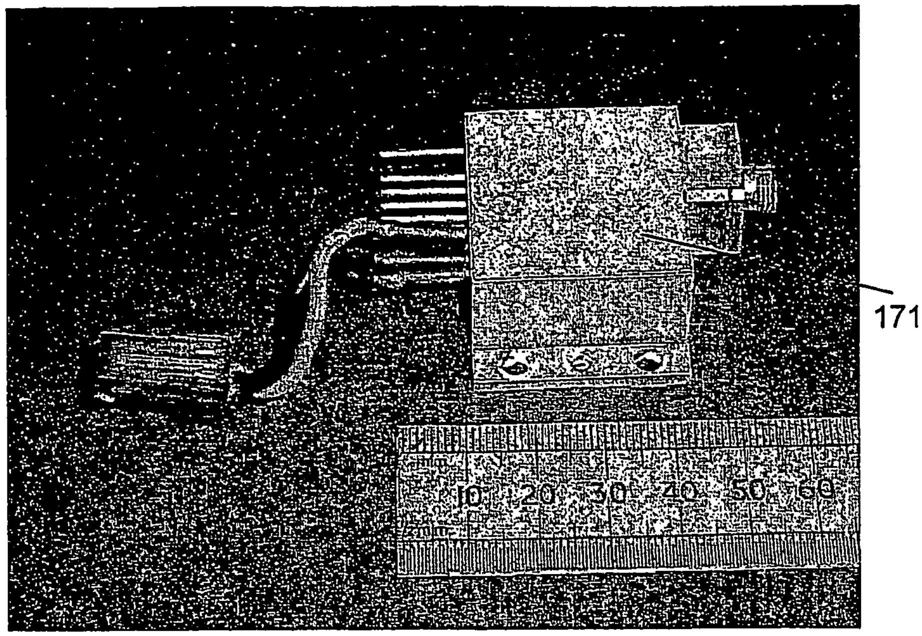

10 20 30 40 50 60
171

FIG 17

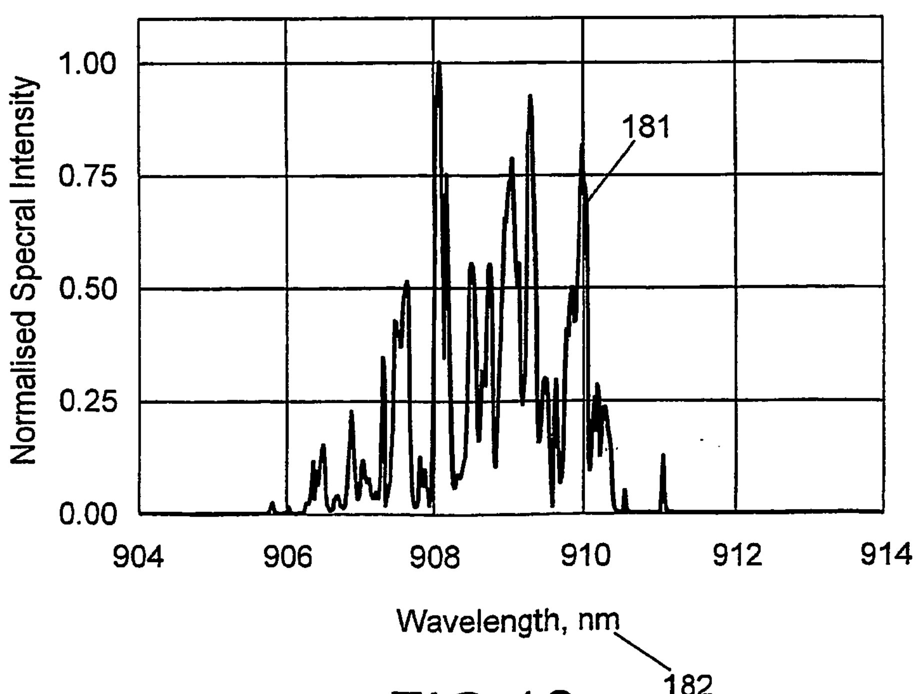

Normalised Specral Intensity
1.00
0.75
0.50
0.25
0.00
904
906
908
910
912
914
Wavelength, nm
181
182

FIG 18

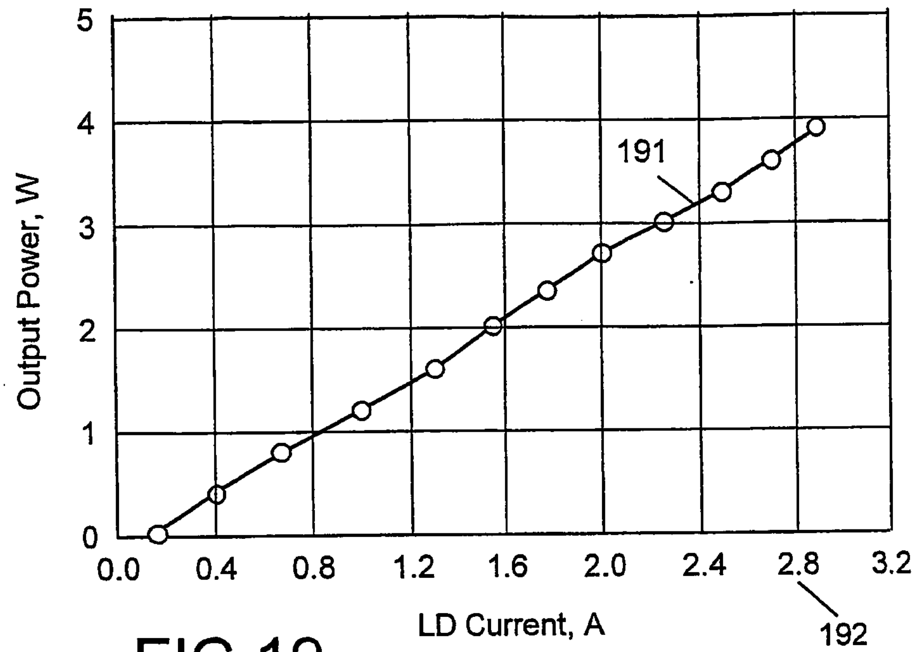


FIG 19

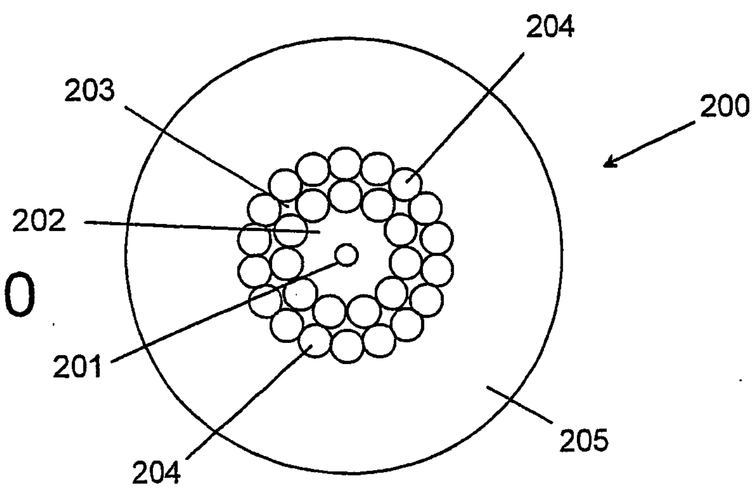


FIG 20

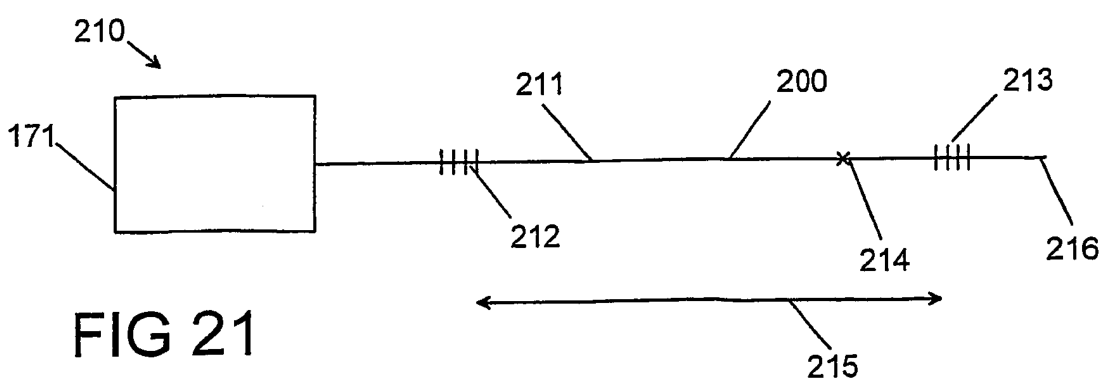


FIG 21

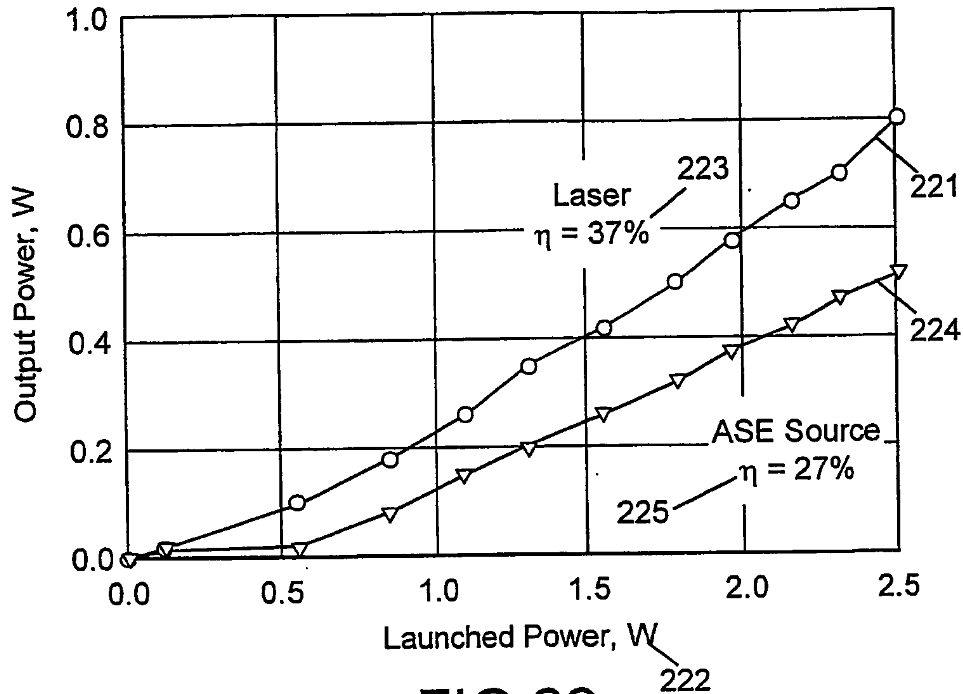

1.0
0.8
0.6
0.4
0.2
0.0
Output Power, W
Laser
η = 37%
223
221
224
ASE Source
η = 27%
225
0.0
0.5
1.0
1.5
2.0
2.5
Launched Power, W
222

FIG 22

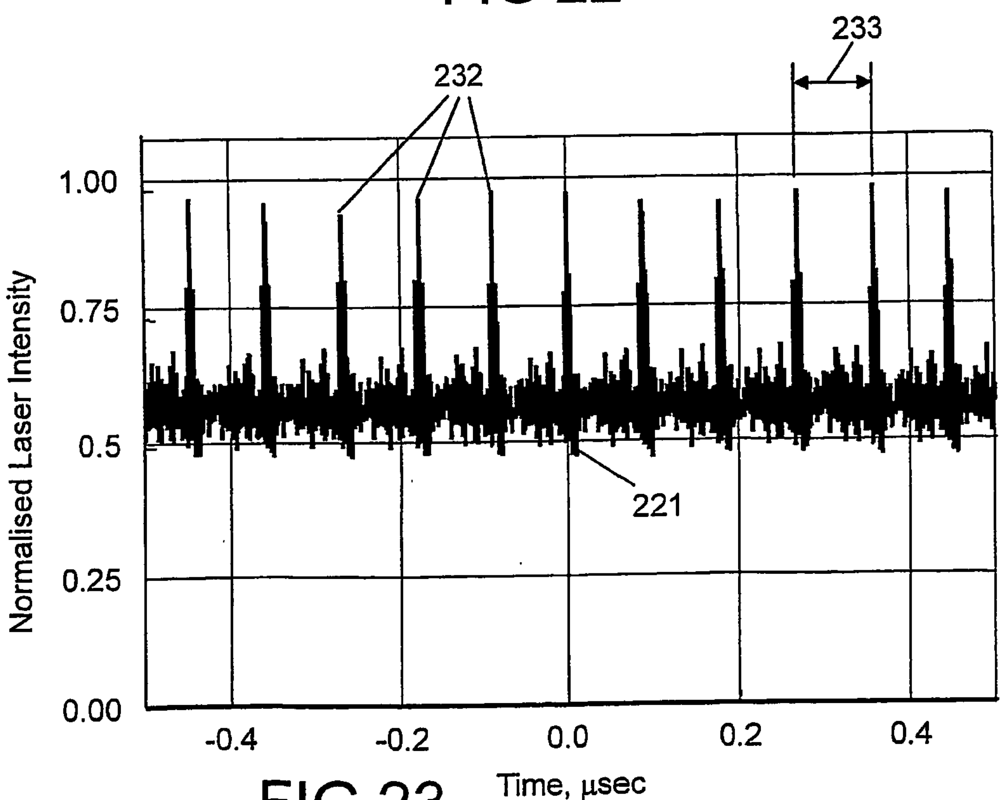

233
232
1.00
0.75
0.5
0.25
0.00
Normalised Laser Intensity
221
-0.4
-0.2
0.0
0.2
0.4
Time, μsec

FIG 23

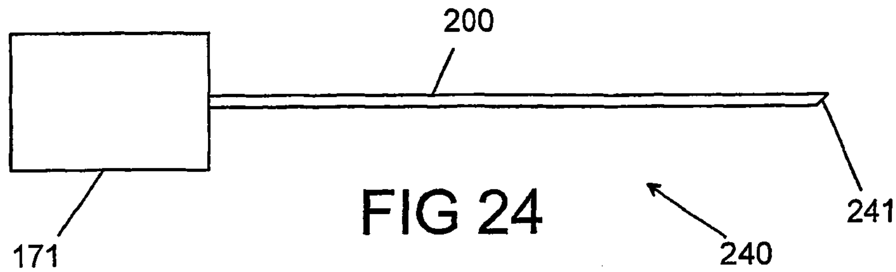

200
171
241
240

FIG 24

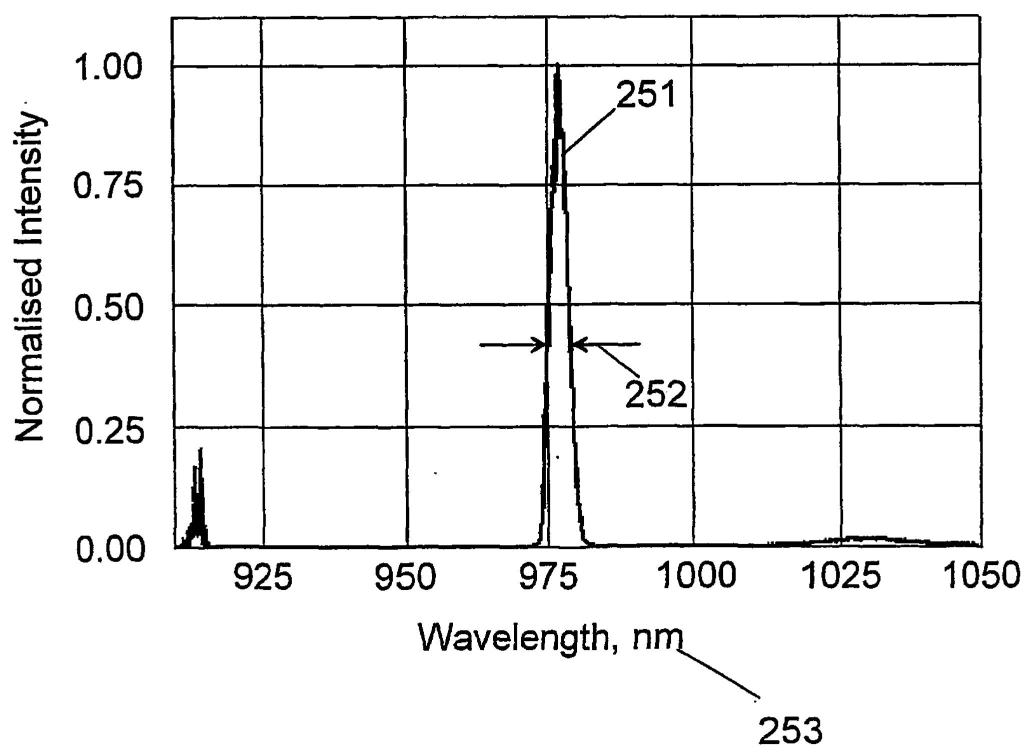

1.00
0.75
0.50
0.25
0.00
Normalised Intensity
251
252
925
950
975
1000
1025
1050
Wavelength, nm
253

FIG 25

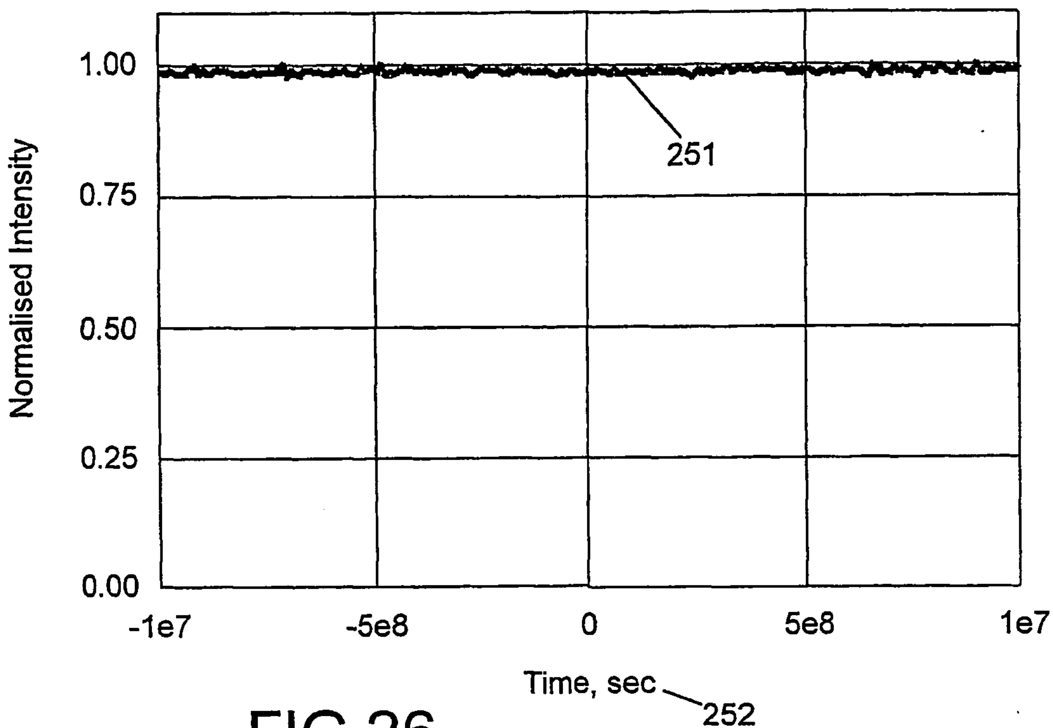

1.00
0.75
0.50
0.25
0.00
Normalised Intensity
251
-1e7
-5e8
0
5e8
1e7
Time, sec
252

FIG 26

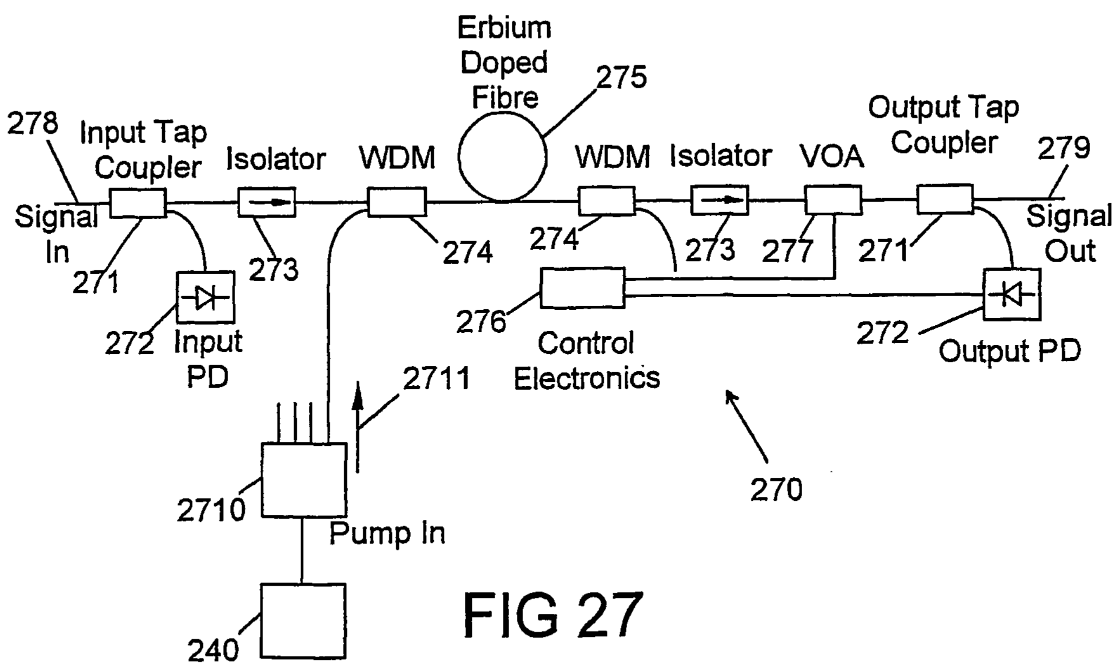

Erbium Doped Fibre
275
278
Input Tap Coupler
Isolator
WDM
WDM
Isolator
VOA
Output Tap Coupler
279
Signal In
Signal Out
271
273
274
274
273
277
271
272
Input PD
276
Control Electronics
272
Output PD
2711
2710
Pump In
270
240

FIG 27

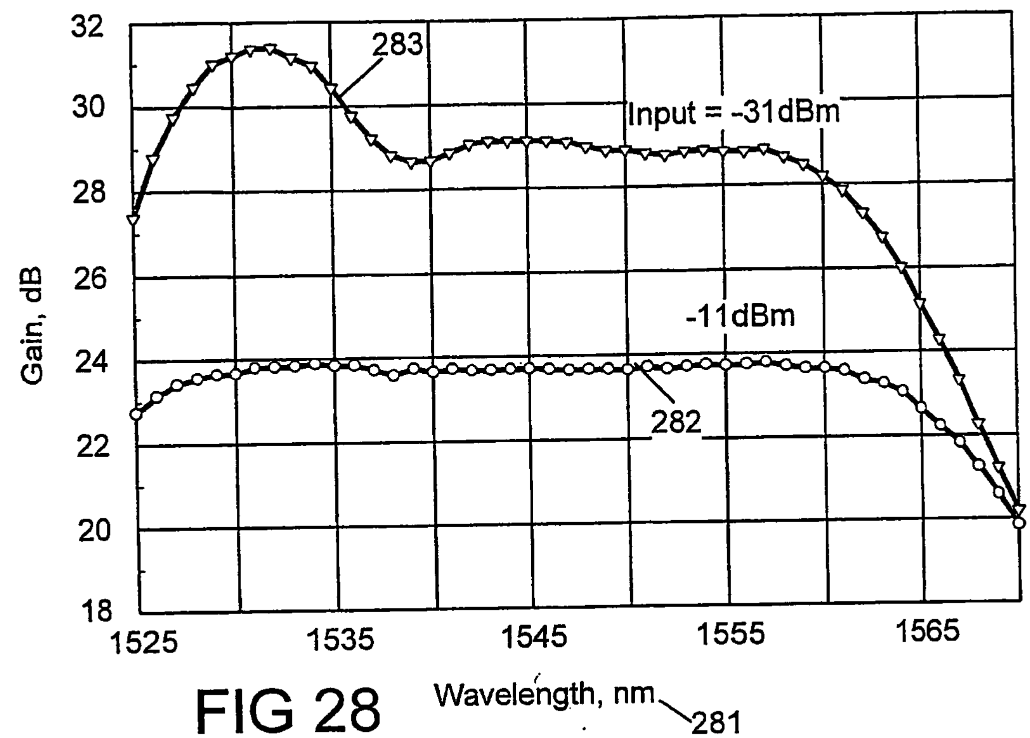

283
Input = -31dBm
-11dBm
282
Gain, dB
32
30
28
26
24
22
20
18
1525
1535
1545
1555
1565
Wavelength, nm
281

FIG 28

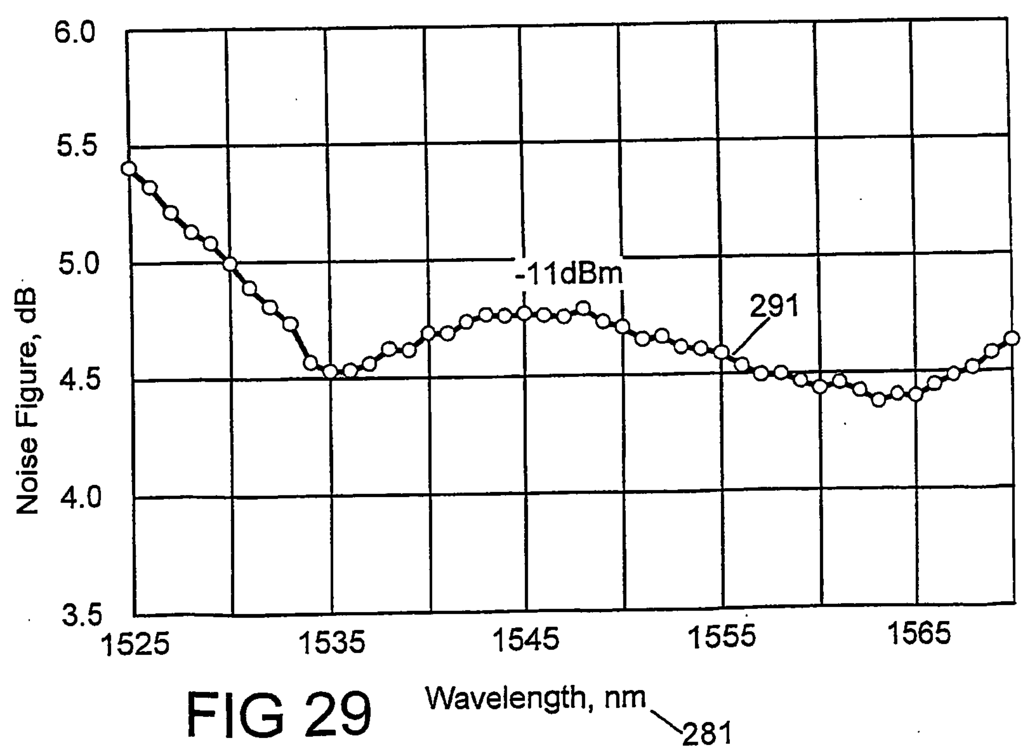

-11dBm
291
Noise Figure, dB
6.0
5.5
5.0
4.5
4.0
3.5
1525
1535
1545
1555
1565
Wavelength, nm
281

FIG 29

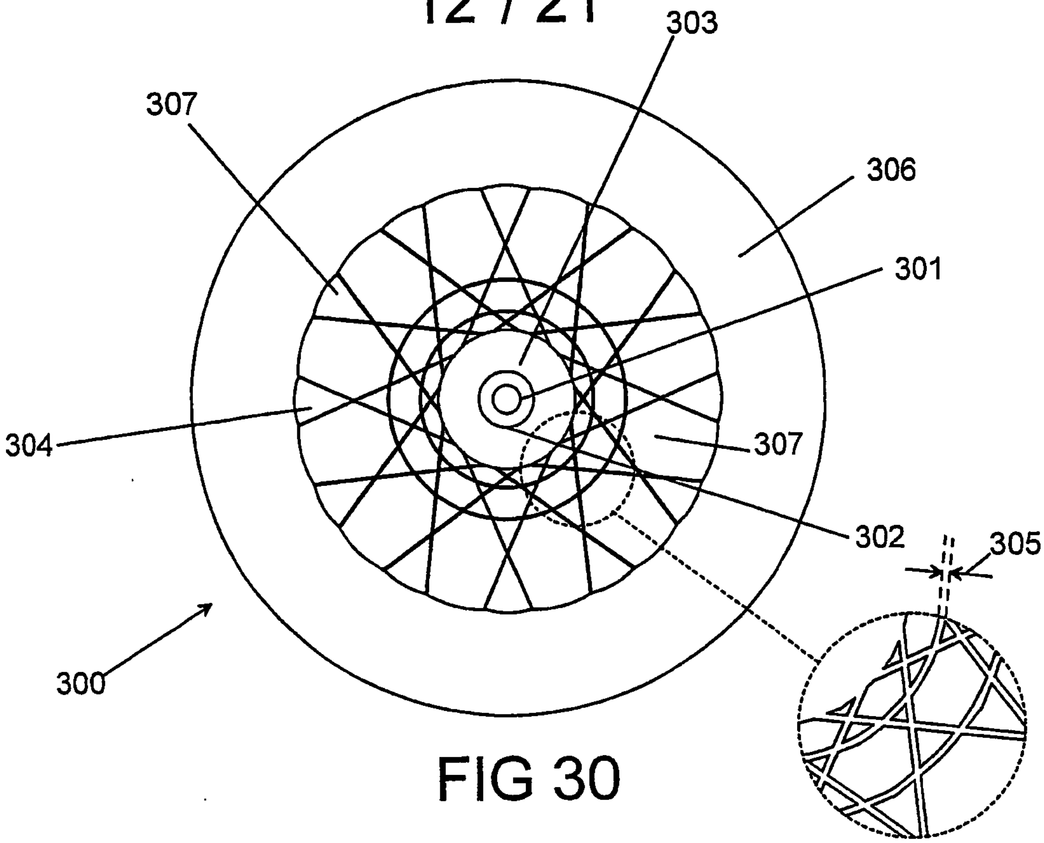


FIG 30

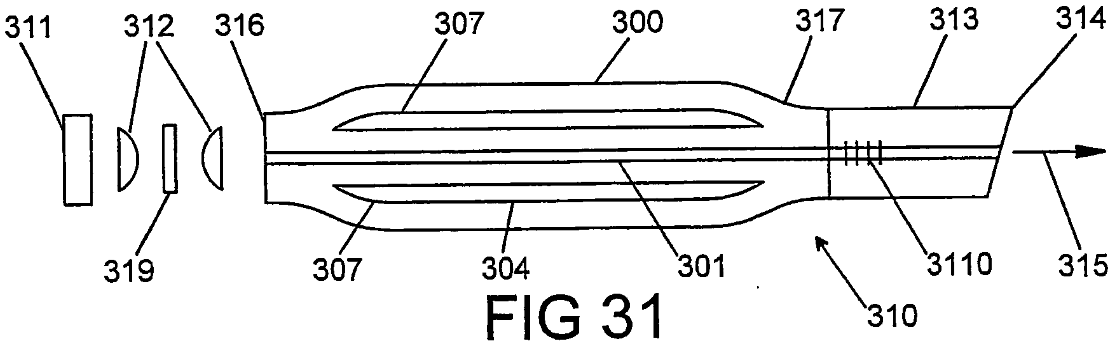


FIG 31

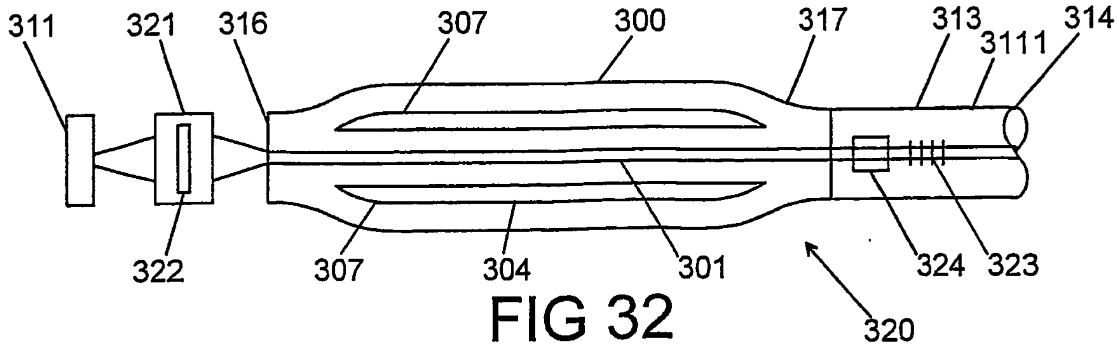


FIG 32

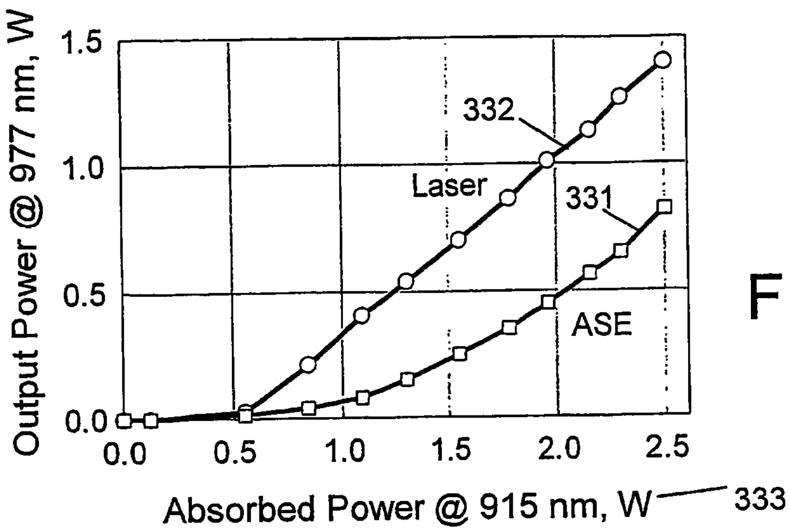


FIG 33

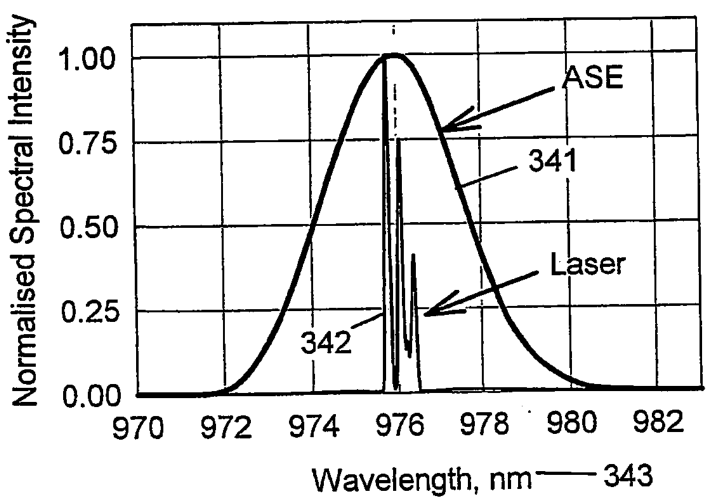


FIG 34

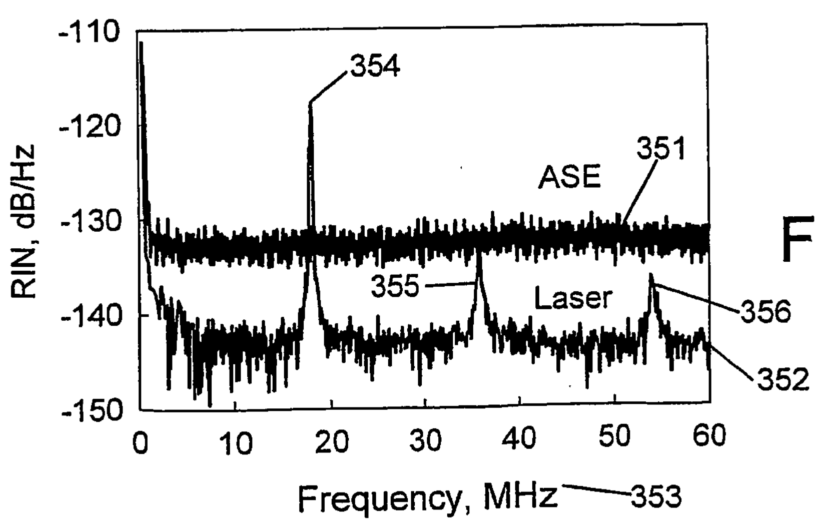


FIG 35

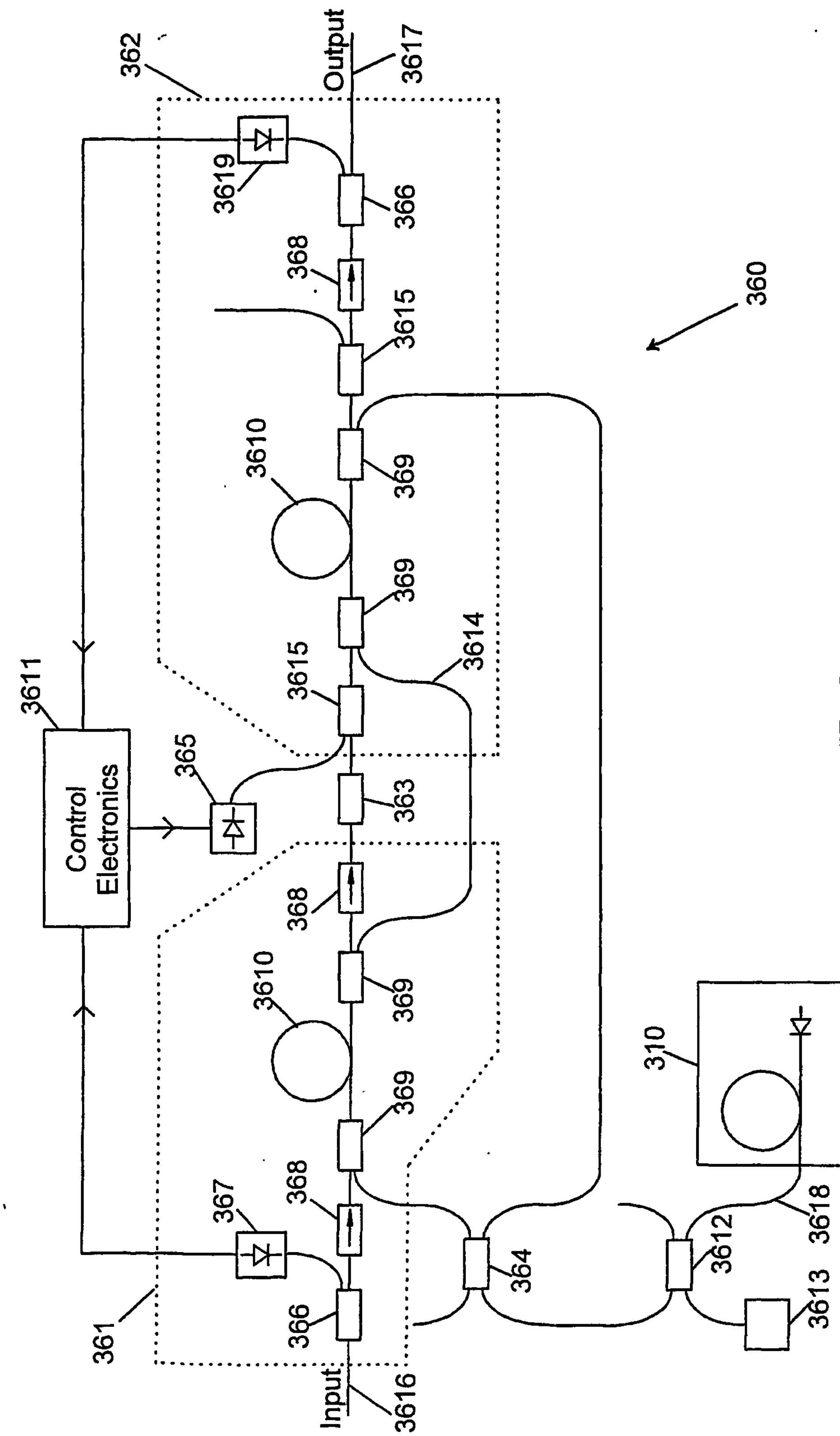

Output
3617
362
3619
366
368
3615
360
3610
369
369
3614
3615
3611
Control Electronics
365
363
368
3610
369
369
310
367
368
364
3612
3618
361
366
3613
Input
3616

FIG 36

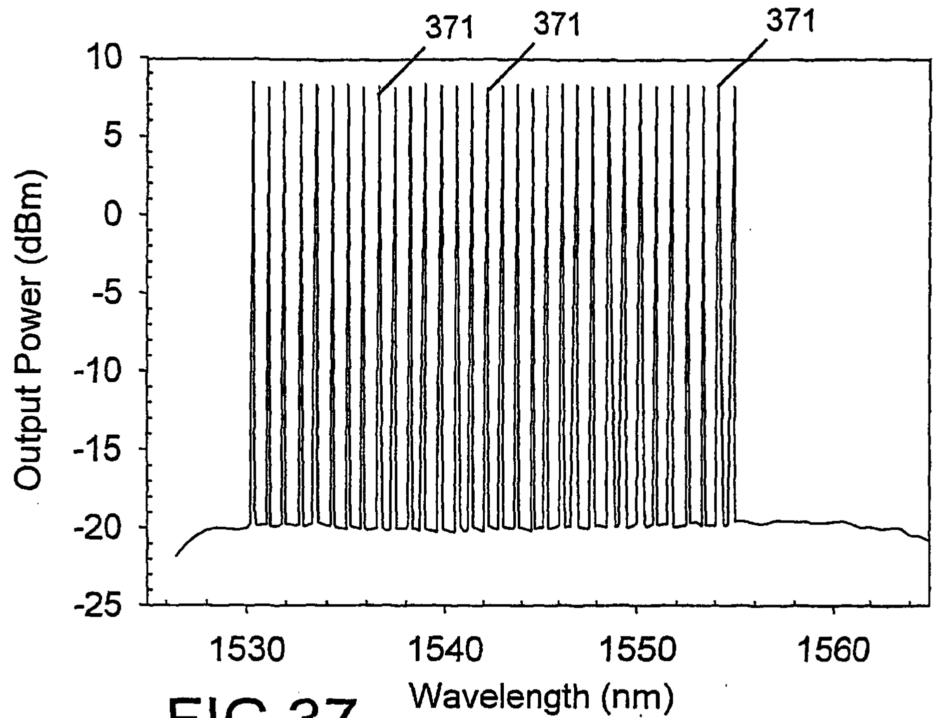

371
371
371
10
5
0
-5
-10
-15
-20
-25
Output Power (dBm)
1530
1540
1550
1560
Wavelength (nm)

FIG 37

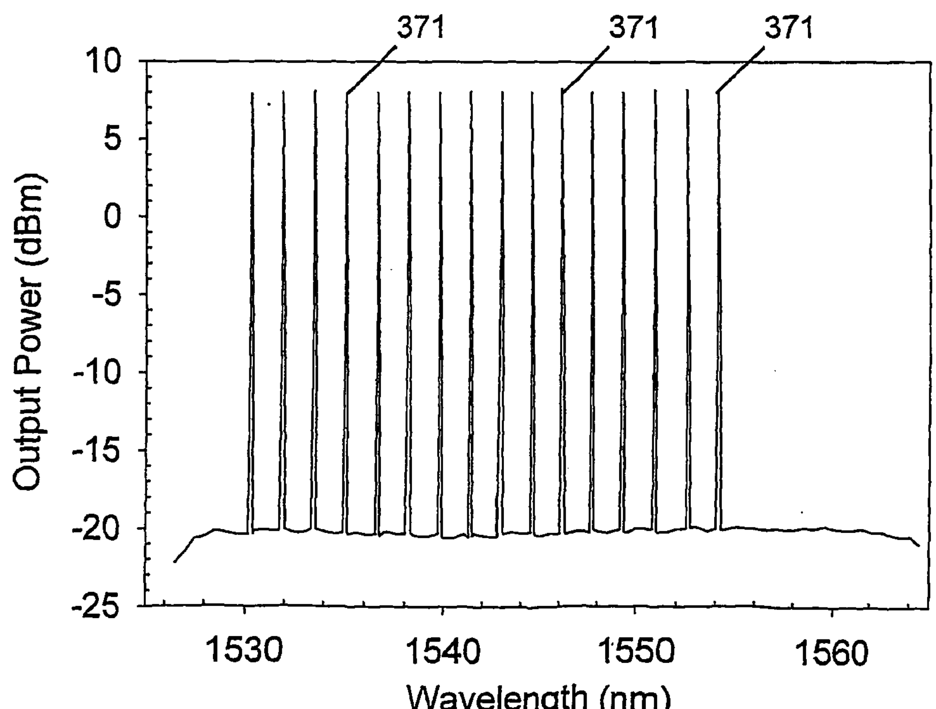

371
371
371
10
5
0
-5
-10
-15
-20
-25
Output Power (dBm)
1530
1540
1550
1560
Wavelength (nm)

FIG 38

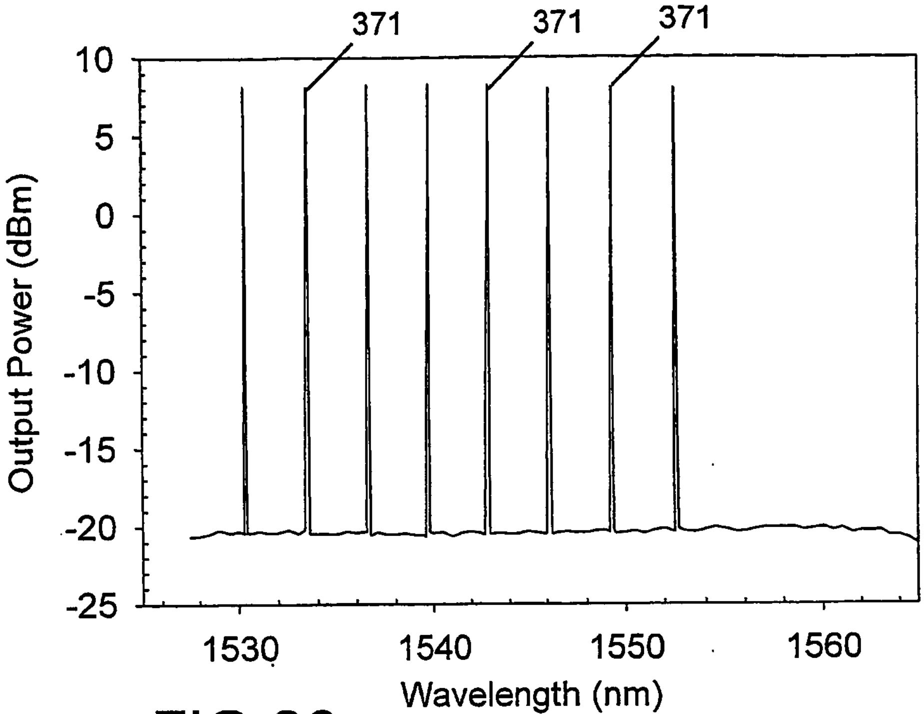

371
371
371
10
5
0
-5
-10
-15
-20
-25
Output Power (dBm)
1530
1540
1550
1560
Wavelength (nm)

FIG 39

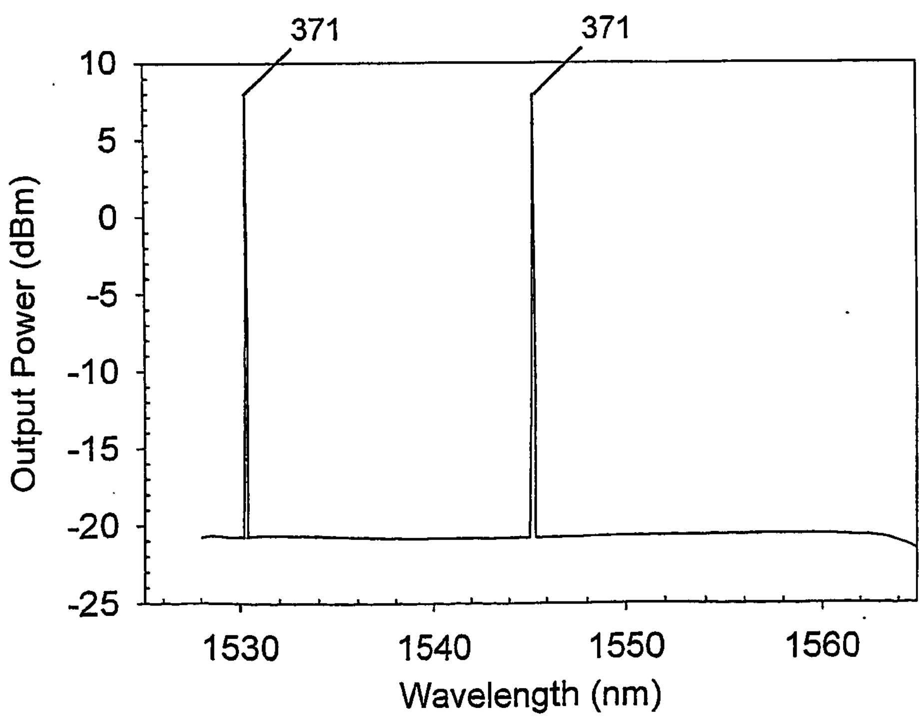

371
371
10
5
0
-5
-10
-15
-20
-25
Output Power (dBm)
1530
1540
1550
1560
Wavelength (nm)

FIG 40

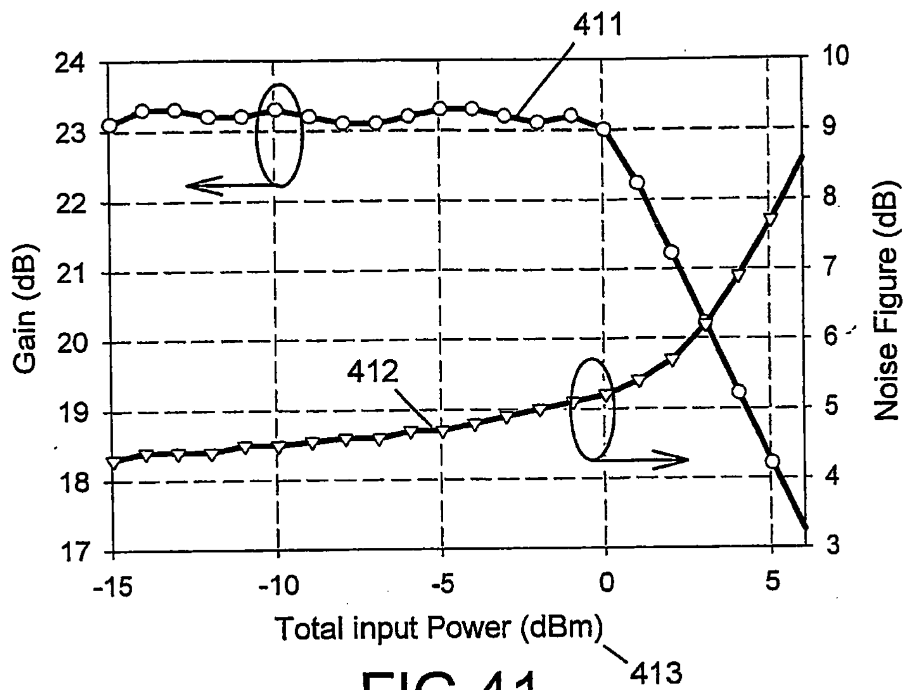

411
412
413
Gain (dB)
Noise Figure (dB)
Total input Power (dBm)
24
23
22
21
20
19
18
17
10
9
8
7
6
5
4
3
-15
-10
-5
0
5

FIG 41

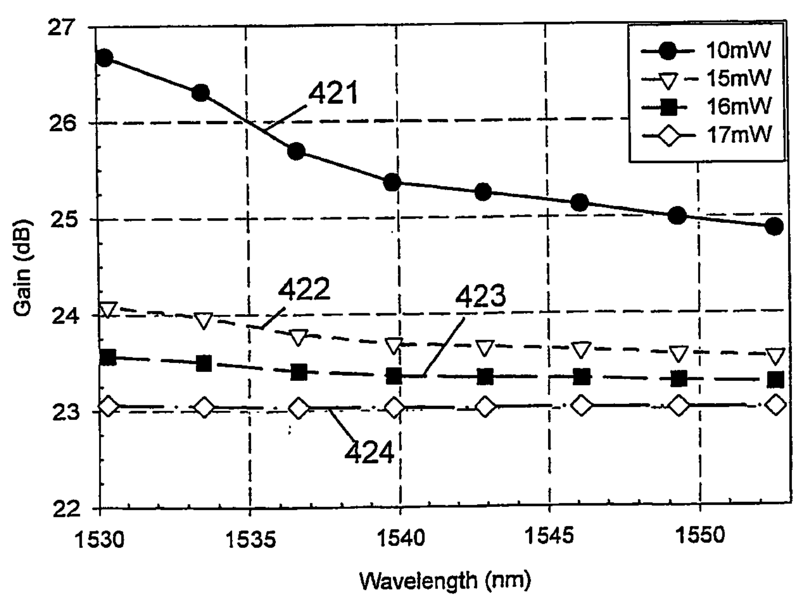

10mW
15mW
16mW
17mW
421
422
423
424
Gain (dB)
Wavelength (nm)
27
26
25
24
23
22
1530
1535
1540
1545
1550

FIG 42

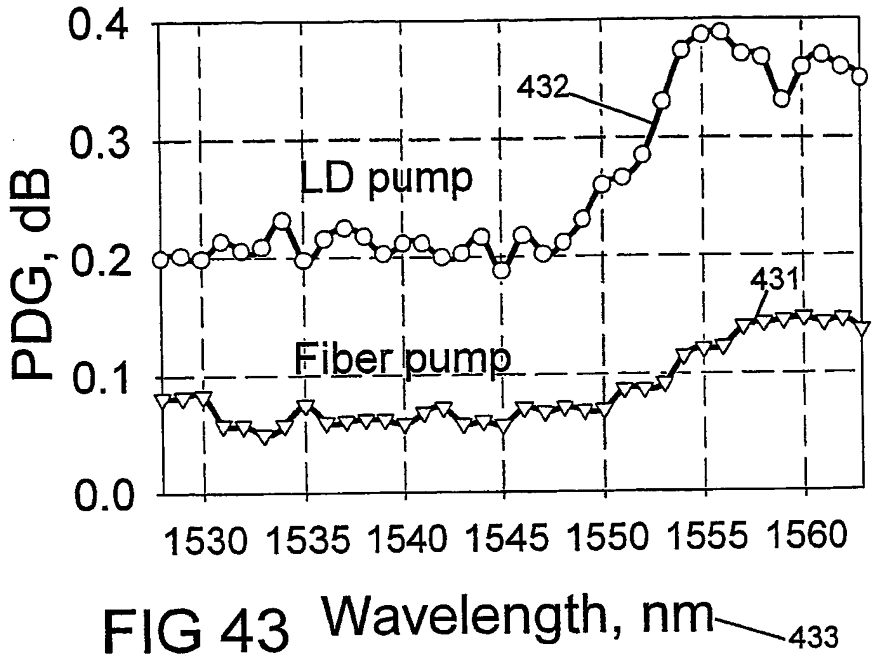

0.4
0.3
0.2
0.1
0.0
PDG, dB
432
LD pump
431
Fiber pump
1530 1535 1540 1545 1550 1555 1560
Wavelength, nm
433

FIG 43

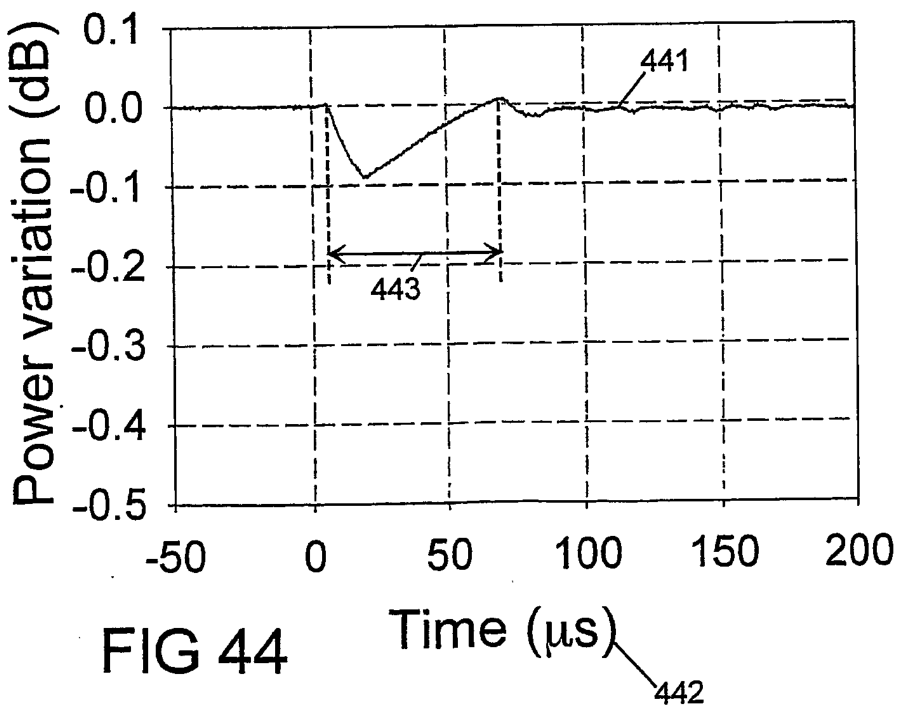

0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Power variation (dB)
441
443
-50 0 50 100 150 200
Time (μs)
442

FIG 44

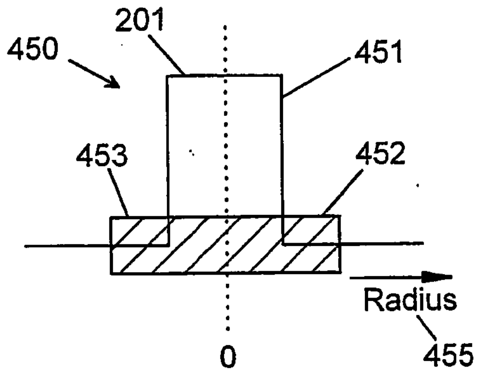


FIG 45

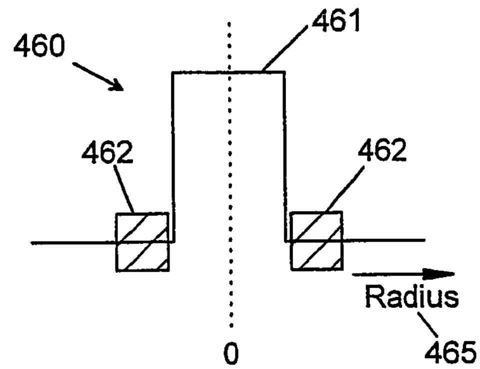


FIG 46

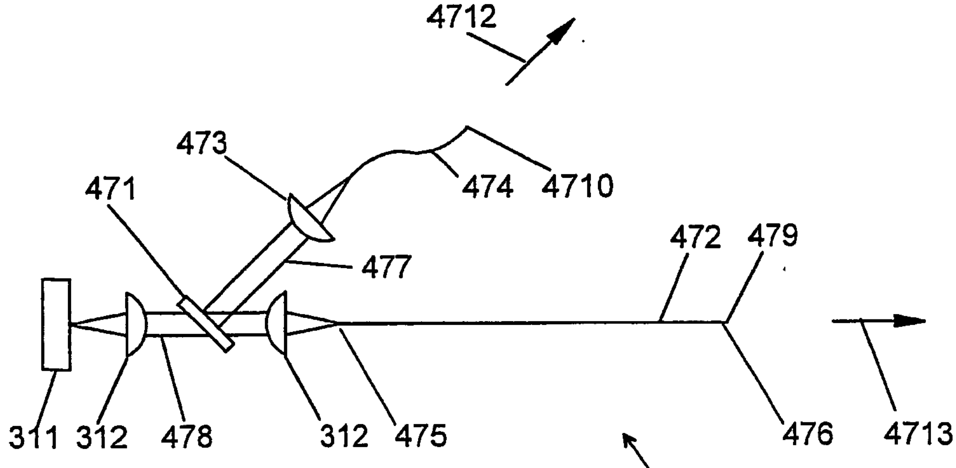


FIG 47

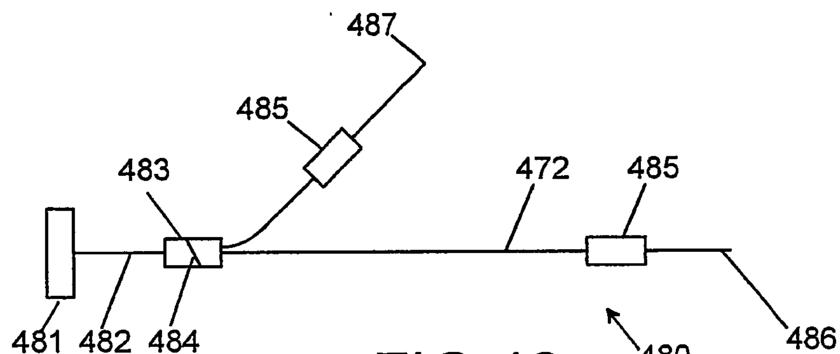


FIG 48

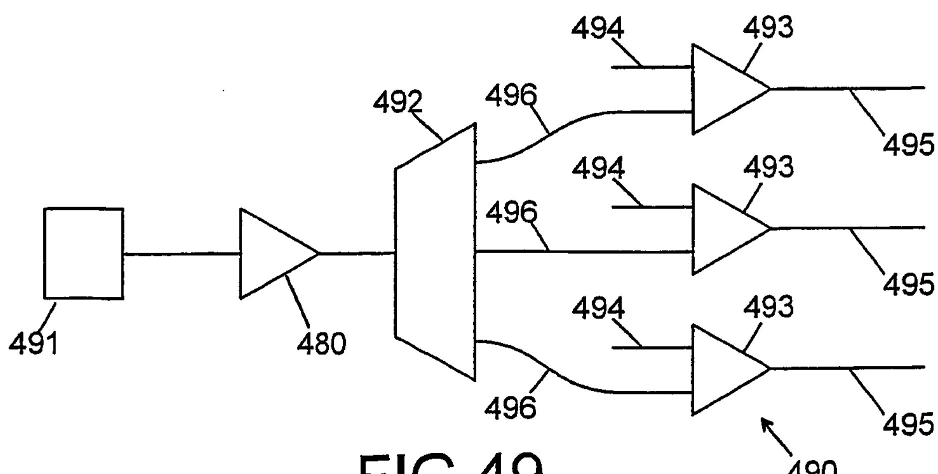


FIG 49

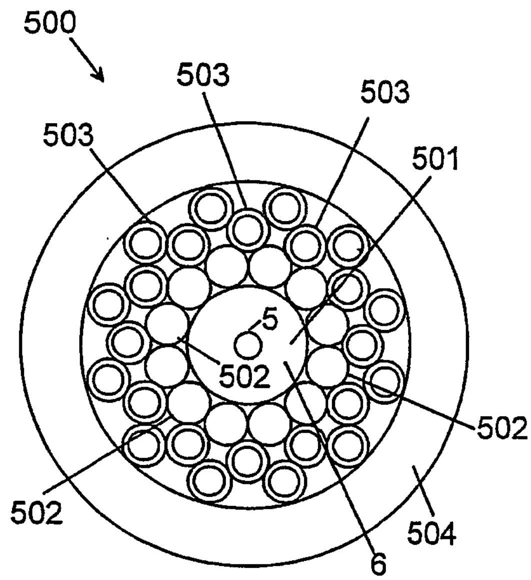


FIG 50

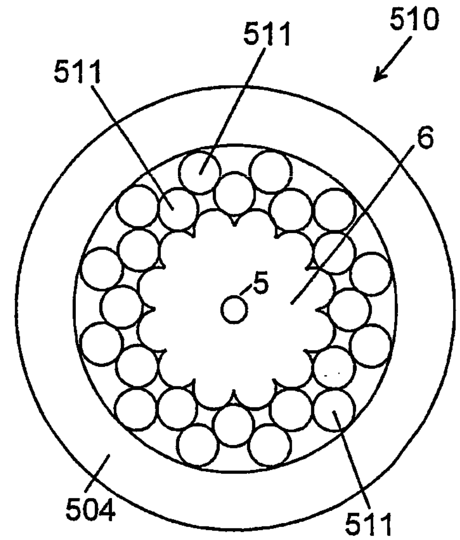


FIG 51

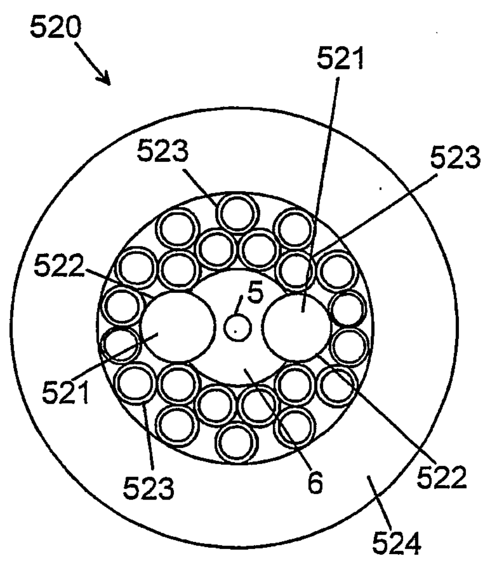


FIG 52

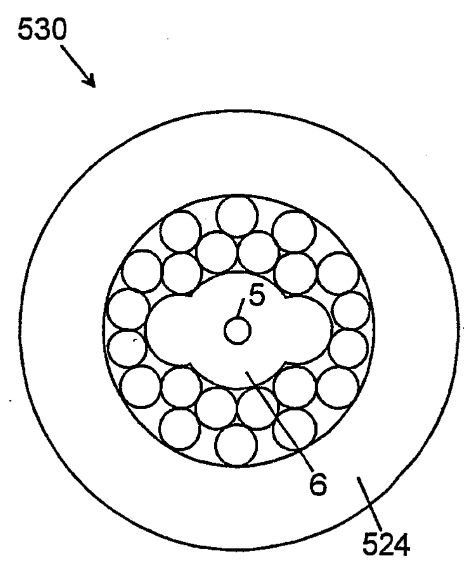


FIG 53